Introduction to Accelerator Physics

Part 3

Pedro Castro / Accelerator Physics Group (MPY)
Zeuthen, 9th August 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Accelerator lectures framework in Summer Student Prog.

<u>12th Aug.:</u> Accelerator R&D at DESY, Anne Oppelt

<u>Today:</u> focus on synchrotrons and synchrotron technology

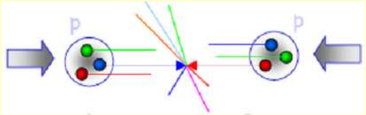
synchrotrons: machines for discoveries

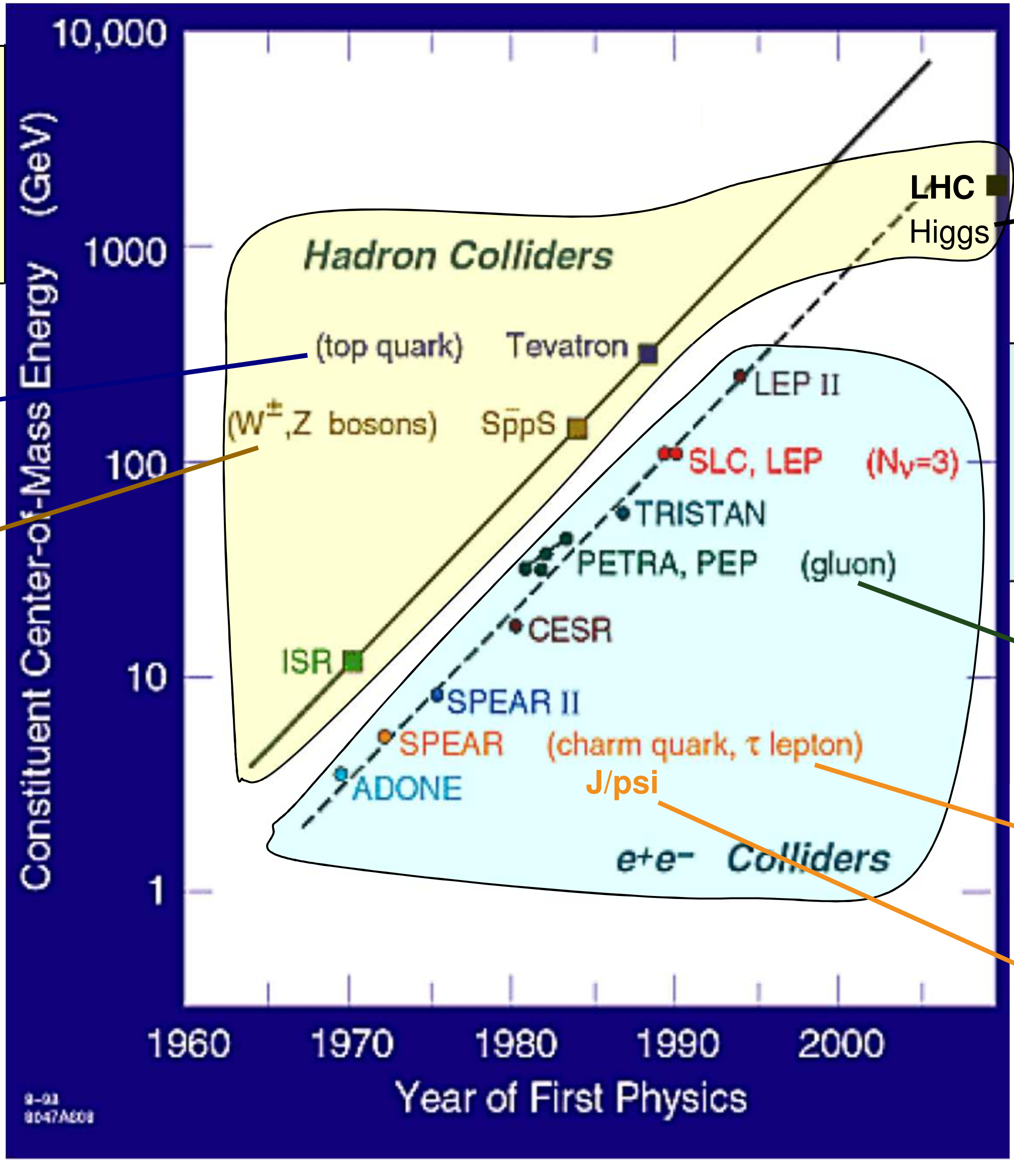
Facility	Particle(s) discovered	Year of discovery	Nobel Price
SPEAR	charm quark	1974	1976
SPEAR	tau lepton	1975	1995
PETRA	gluon	1979	
S$\bar{p}$pS	$W^{\pm}, Z$ bosons	1983	1984
SLC, LEP	$N_\nu = 3$		
Tevatron	top quark	1995	
LHC	Higgs	2012	2013

Main HEP discoveries at synchrotrons in the last 50 years

hadron colliders:

$E_{cm} / 3$ quarks



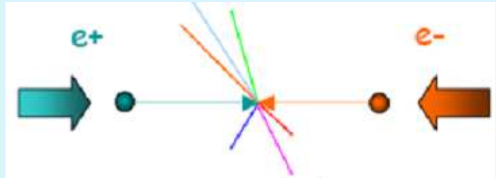


discovered 1995

discovered 1983
NP 1984

discovered 2012
NP 2013

e+e- colliders:



discovered 1979

discovered 1975
NP 1995

discovered 1974
NP 1976

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hadron colliders:
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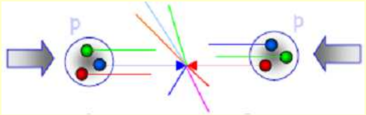

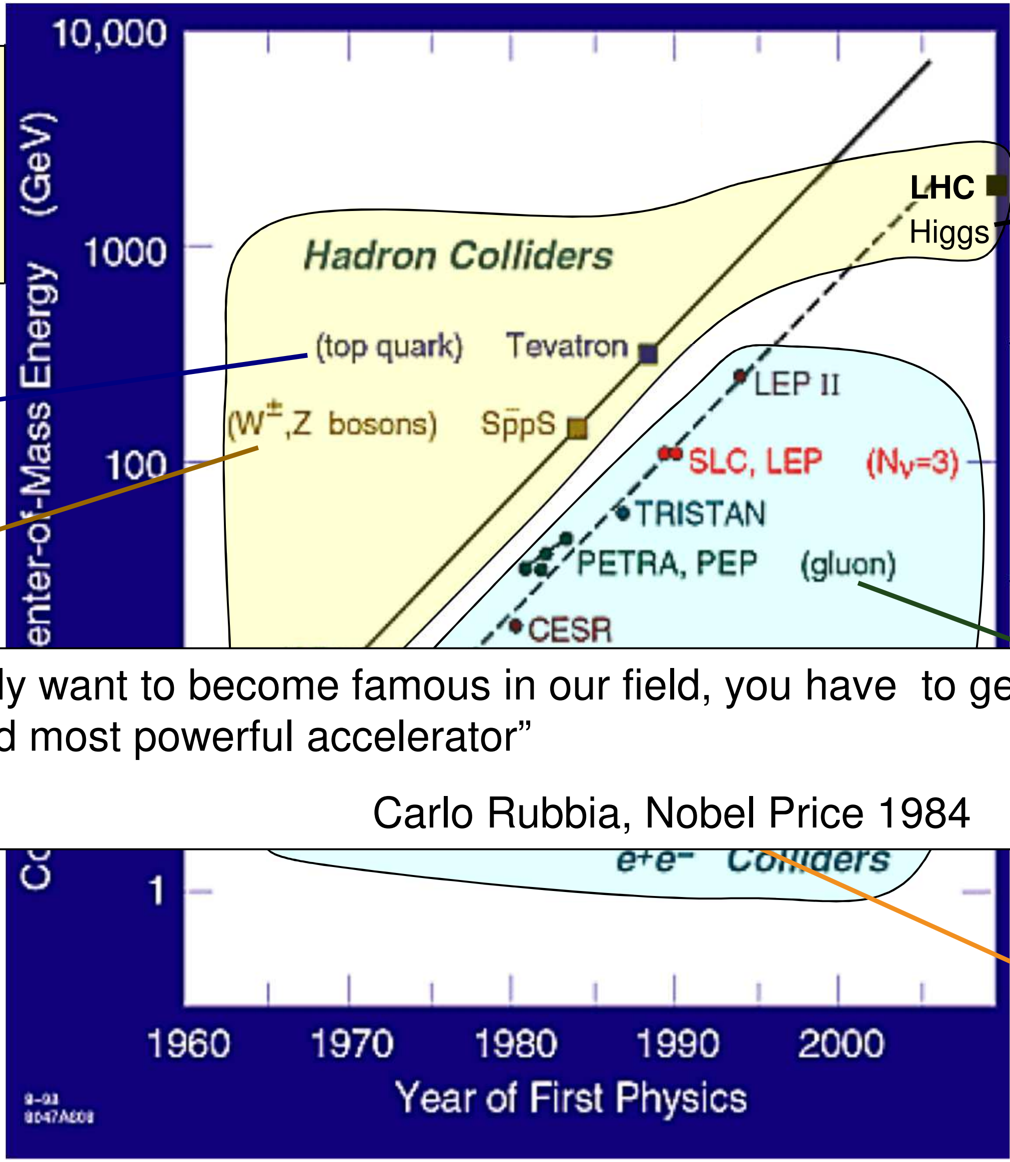

discovered 2012
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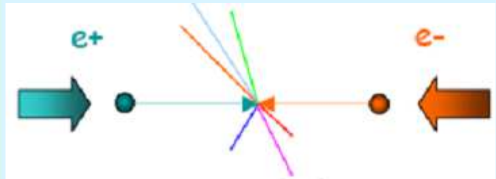

discovered 1983
NP 1984

"if you really want to become famous in our field, you have to get yourself the biggest and most powerful accelerator"

Carlo Rubbia, Nobel Price 1984

discovered 1975
NP 1995

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NP 1976

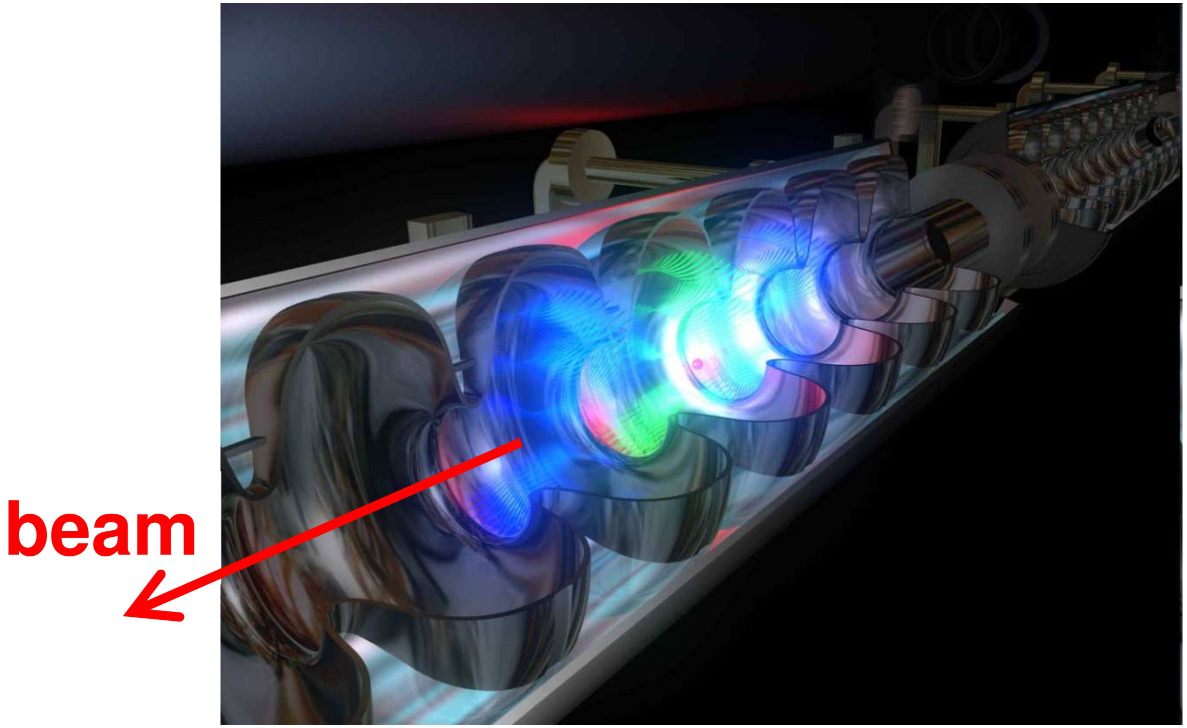
Scope of this lecture:

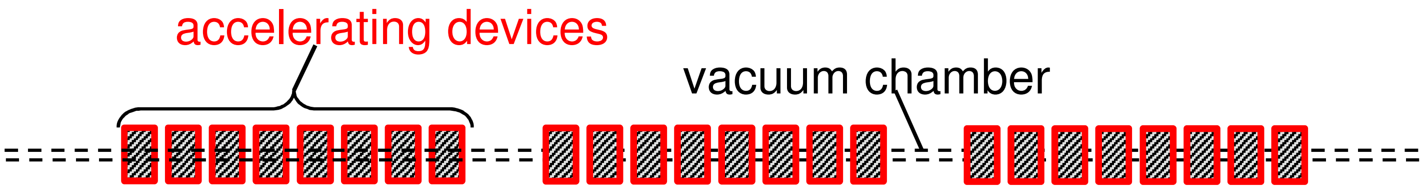
1. Synchrotrons: key components and their challenges to reach high energies:

- Dipole magnetic fields
- Superconducting dipoles
- Quadrupole magnets to focus beams

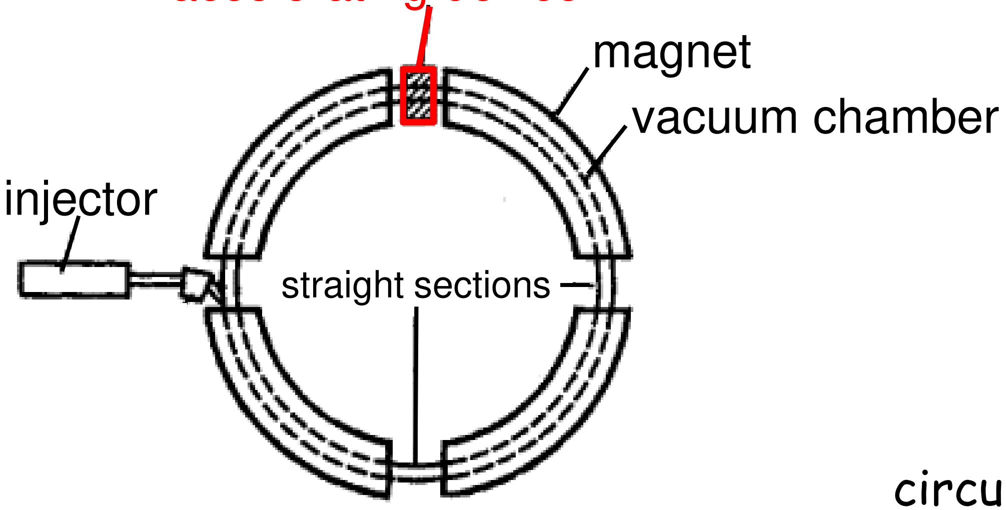
2. Synchrotrons and Linear Accelerators:

- Acceleration using radio-frequency electomagnetic fields





linear accelerator (linac)



circular accelerator: synchrotron

Motion in electric and magnetic fields

Equation of motion under Lorentz Force

$$\frac{d\vec{p}}{dt} = \vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$$

magnetic field

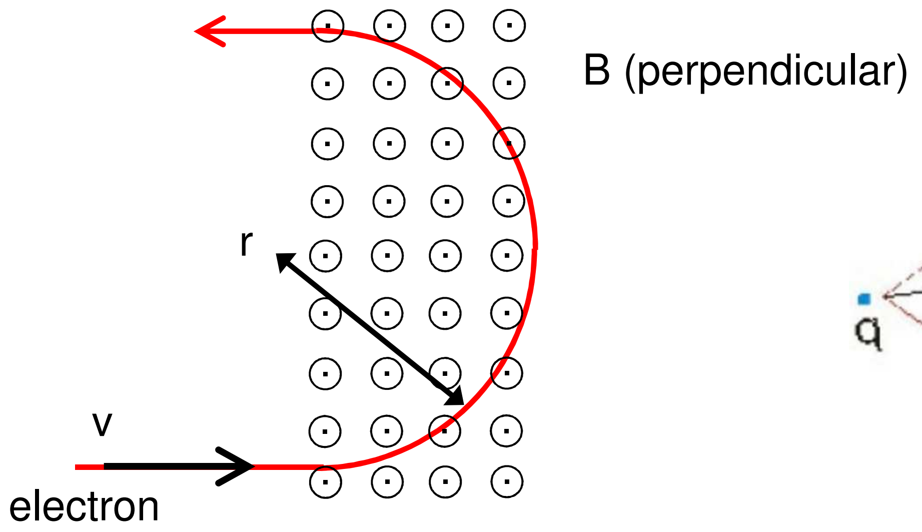
momentum charge velocity electric field

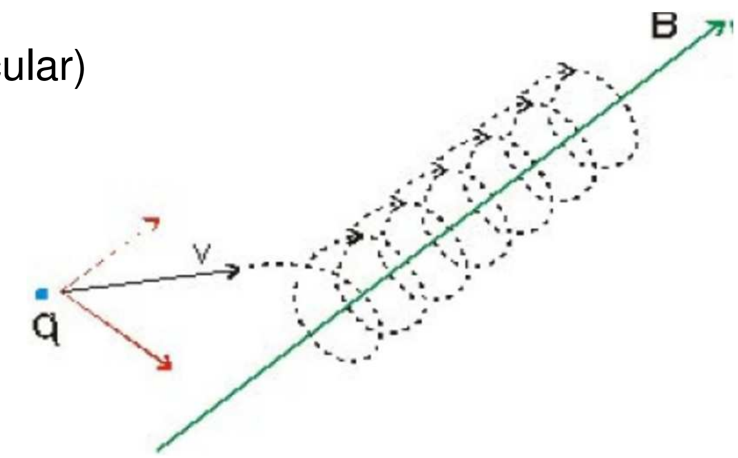
$\underbrace{\text{momentum} \quad \text{charge} \quad \text{velocity}}_{\text{of the particle}}$

Motion in magnetic fields

if the electric field is zero ($\vec{E} = 0$), then

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B} \quad \rightarrow \quad \vec{F} \perp \vec{v}$$





Magnetic fields <u>do not change</u> the particles energy

Motion in magnetic fields

if the electric field is zero (E=0), then

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B}$$

$$E^2 = \vec{p}^2 c^2 + E_0^2$$

energy-momentum relation in special relativity

total energy

energy at rest

momentum

Motion in magnetic fields

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$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B}$$

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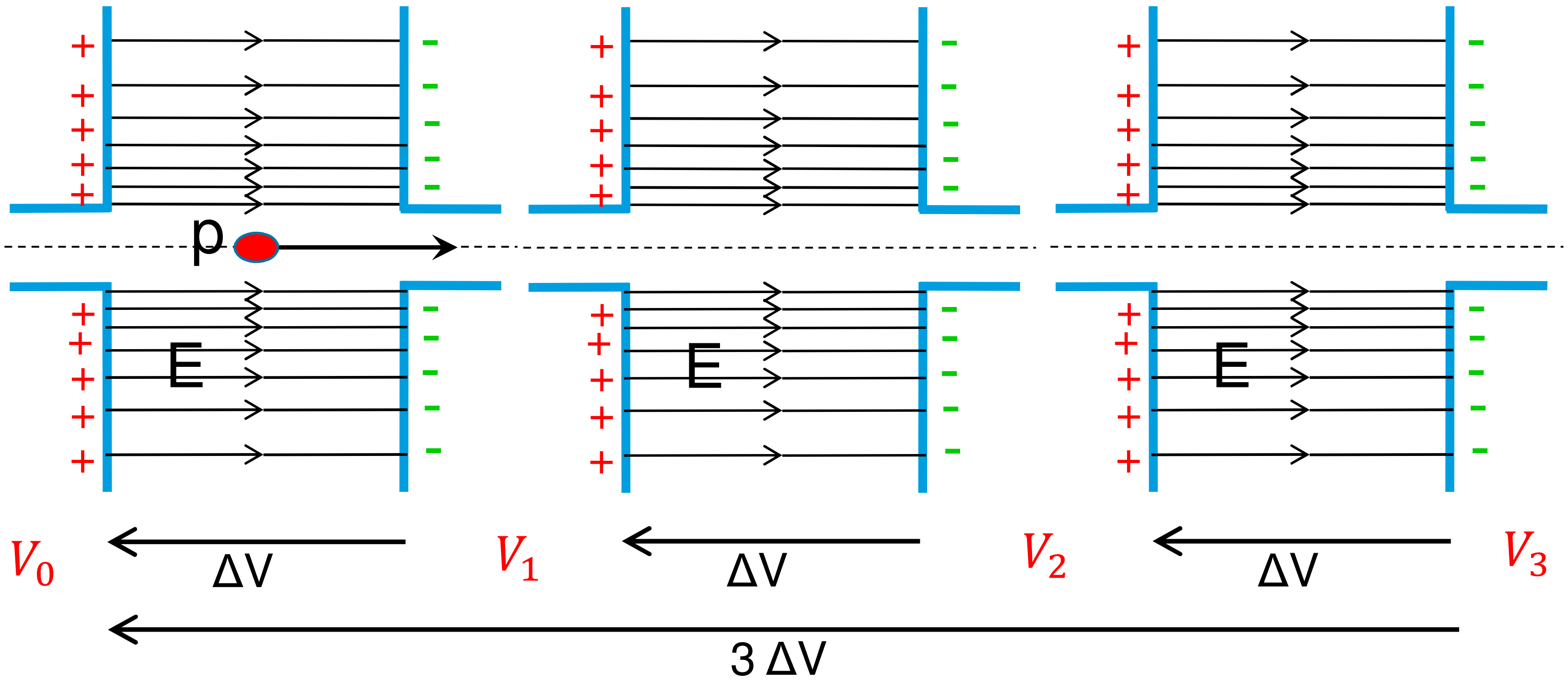
$$E\frac{dE}{dt} = c^2 \vec{p}\frac{d\vec{p}}{dt} = c^2 q\vec{p}(\vec{v} \times \vec{B}) = c^2 q|\vec{p}|\,|\vec{v} \times \vec{B}|\,\cos\emptyset = 0$$

since $\vec{v} \times \vec{B} \perp \vec{v}$ ➔ $\emptyset = 90°$

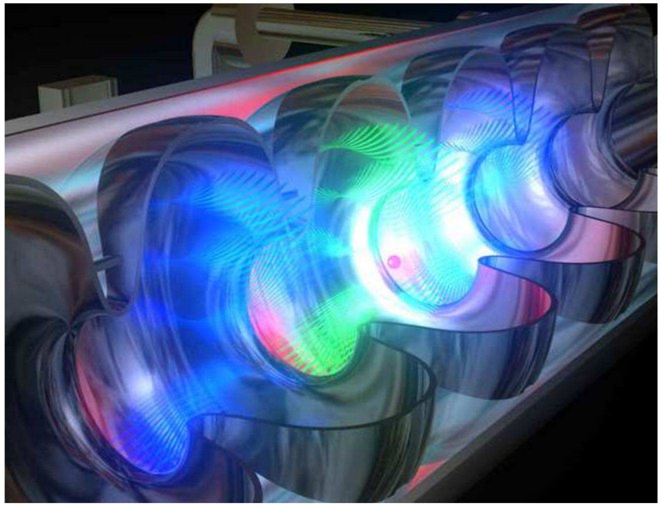
Magnetic fields <u>do not change</u> the particles energy, only electric fields do !

acceleration with DC electric fields

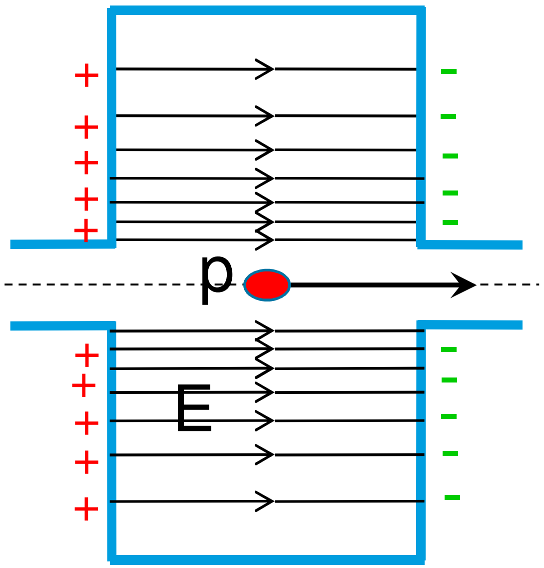


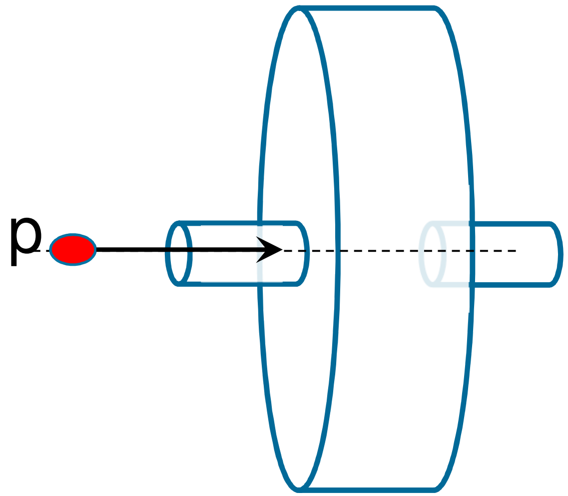
In general:

- Static magnetic fields → to guide (bend + focus) particle beams
- Static electric fields → accelerate particle beams (low energy)
- Radio-frequency EM fields → accelerate particle beams (high E)

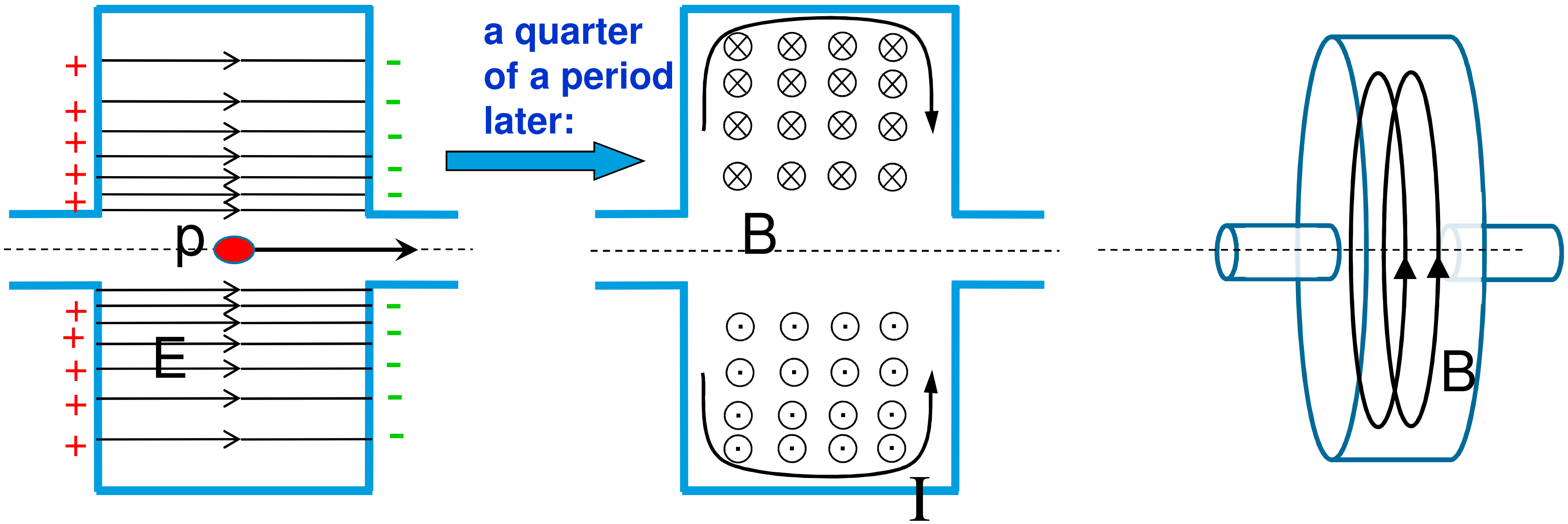


acceleration with RF (radio-frequency) electric fields





RF cavity basics: a cylindrical cavity



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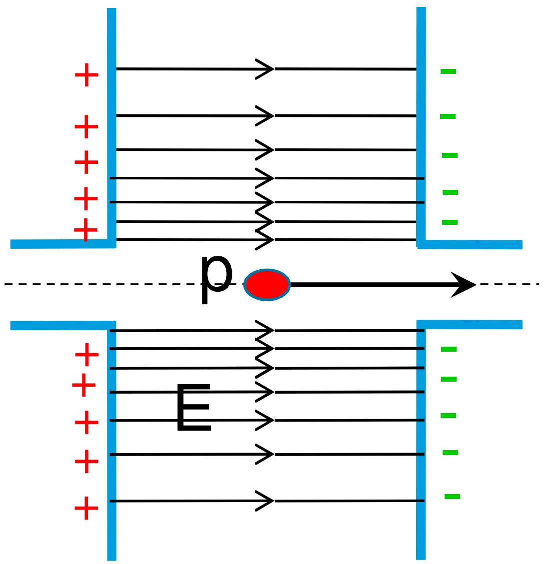
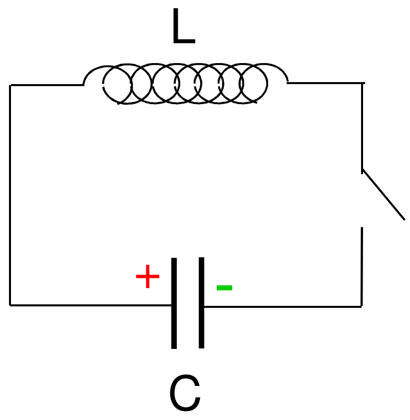


LC circuit (or resonant circuit) analogy:



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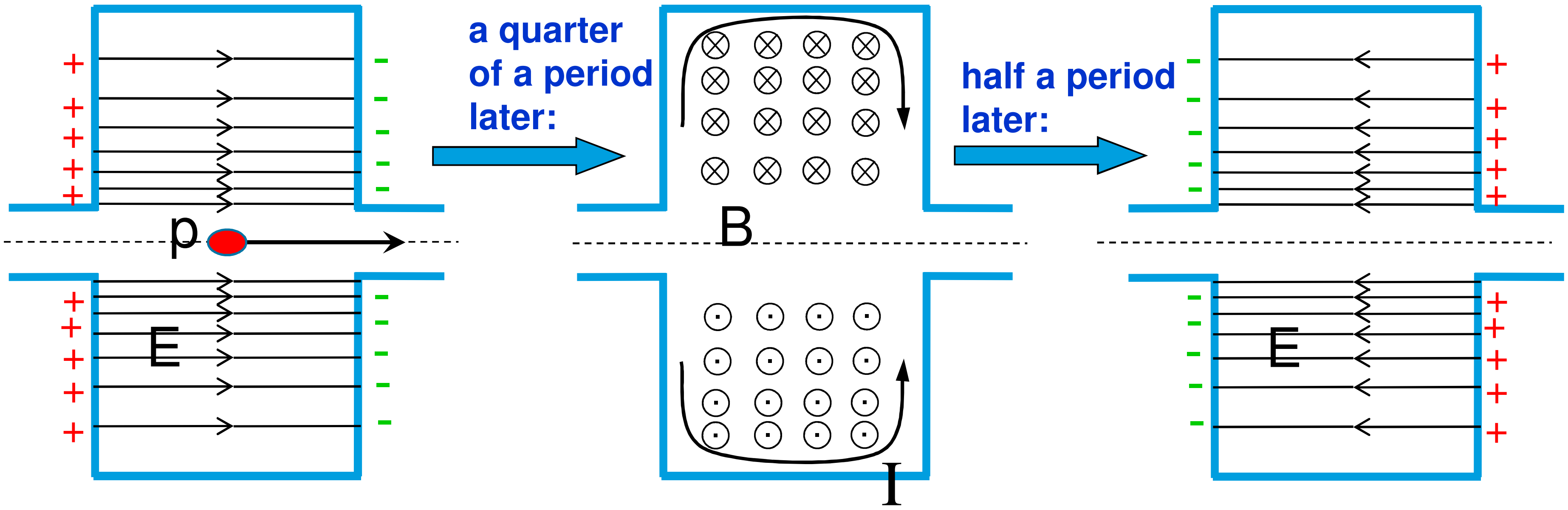

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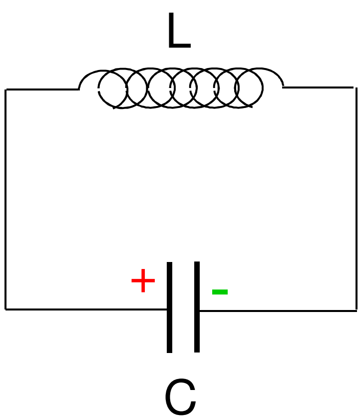
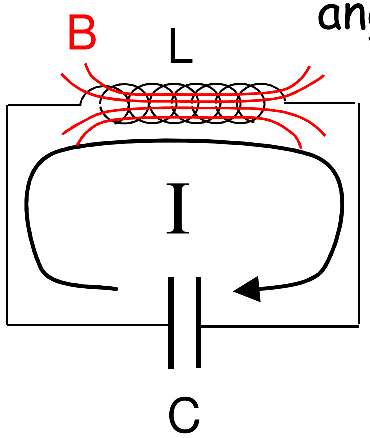
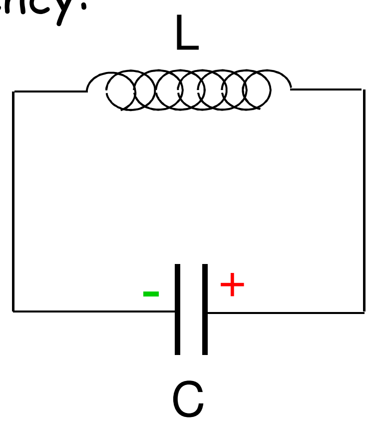


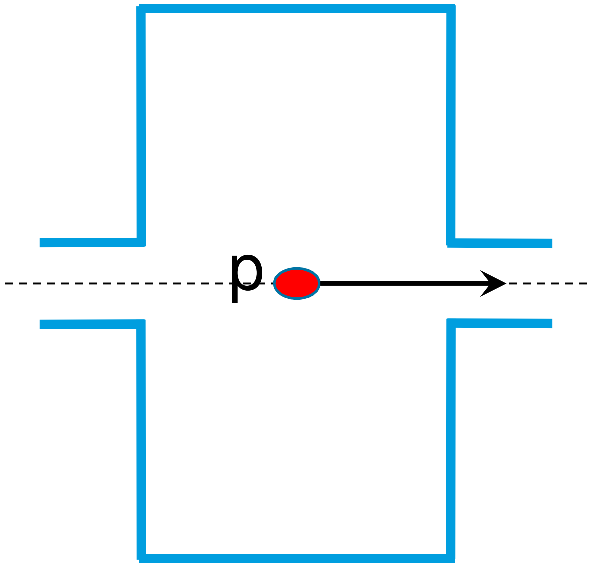


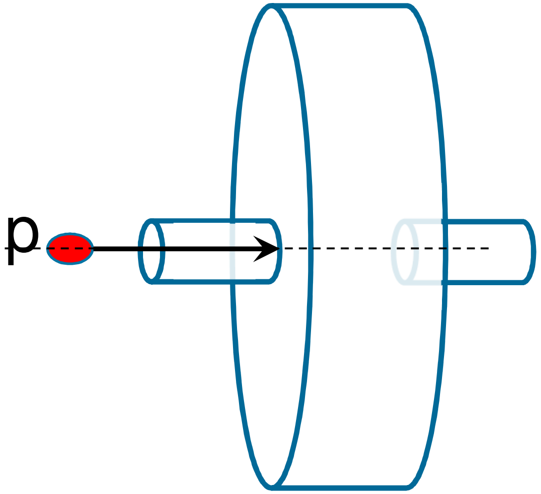
angular frequency:

$$\omega = \frac{1}{\sqrt{LC}}$$



RF cavity basics: the pill box cavity





pill boxes

Equations for the electric and magnetic fields in a pill box cavity

Maxwell's equations
(differential formulation in SI units)

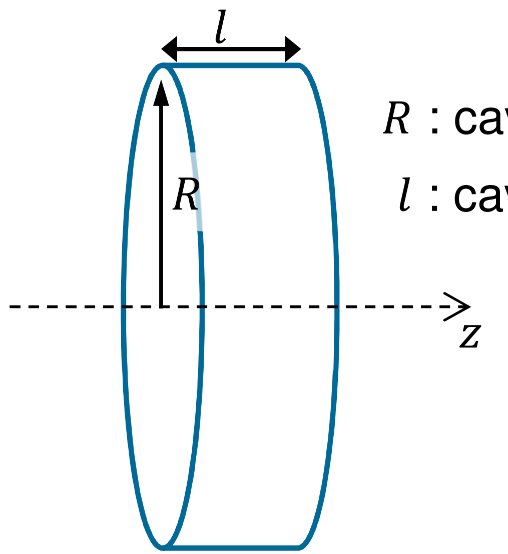
$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J} + \mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}$$

+ boundary conditions



R : cavity radius

l : cavity length

set of solutions with $B_z = 0$ (that is, $\vec{B}$ is transverse)

TM modes
(transverse magnetic modes)

~~set of solutions with $E_z = 0$ (that is, $\vec{E}$ is transverse)~~

~~TE modes~~
~~(transverse electric modes)~~

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$$\begin{cases} E_z = E_0 J_m\left(x_{mn}\frac{r}{R}\right)\cos m\theta \cos\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ E_r = -\frac{p\pi}{l}\frac{R}{x_{mn}}E_0 J'_m\left(x_{mn}\frac{r}{R}\right)\cos m\theta \sin\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ E_\theta = -\frac{p\pi}{l}\frac{mR^2}{x_{mn}{}^2\, r}E_0 J_m\left(x_{mn}\frac{r}{R}\right)\sin m\theta \sin\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ B_z = 0 \\ B_r = -j\omega\frac{mR^2}{x_{mn}{}^2\, rc^2}E_0 J_m\left(x_{mn}\frac{r}{R}\right)\sin m\theta \cos\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ B_\theta = -j\omega\frac{R}{x_{mn}c^2}E_0 J'_m\left(x_{mn}\frac{r}{R}\right)\cos m\theta \cos\left(\frac{p\pi}{l}z\right)e^{j\omega t} \end{cases}$$

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B_z = 0 \\
B_r = \underline{-j\omega}\frac{mR^2}{x_{mn}{}^2 rc^2}E_0 J_m\left(x_{mn}\frac{r}{R}\right)\sin m\theta \cos\left(\frac{p\pi}{l}z\right)\boxed{e^{j\omega t}} \\
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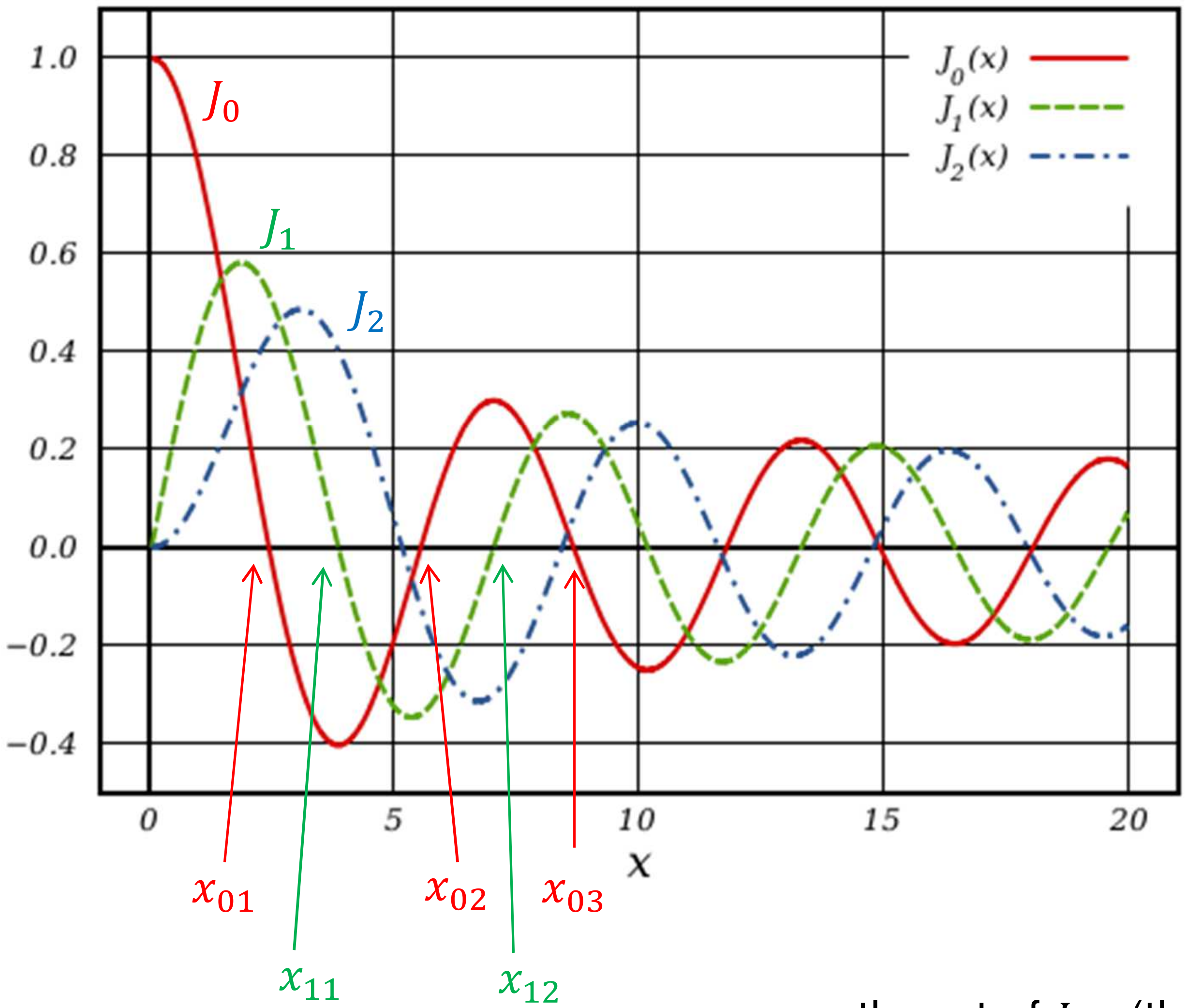

m	x_{m1}	x_{m2}	x_{m3}
0	2.405	5.520	8.654
1	3.832	7.016	10.173
2	5.136	8.417	11.620

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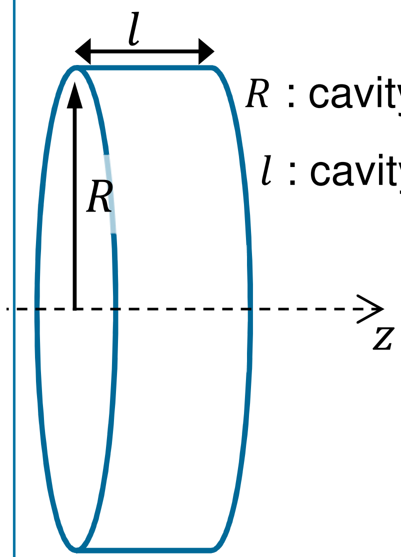

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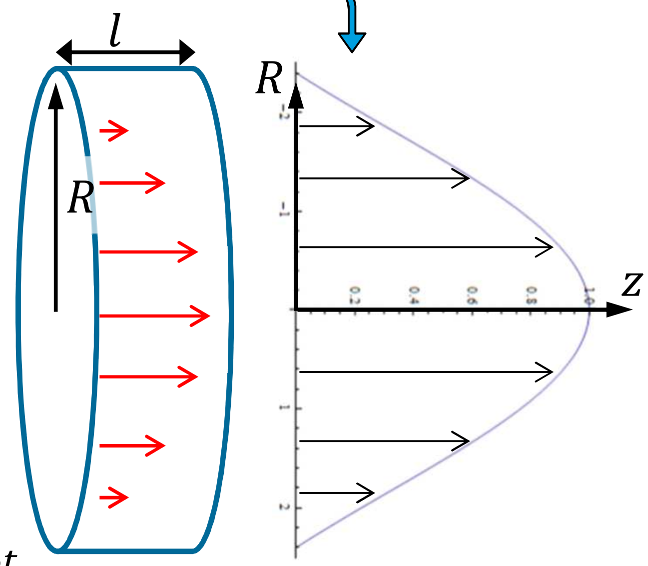
fundamental solution with $B_z = 0$ (that is, $\vec{B}$ is transverse)

$$E_z = E_0 J_0\left(x_{01}\frac{r}{R}\right) e^{j\omega t}$$



$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

$$B_\theta = j\omega \frac{R}{x_{01}c^2} E_0 J_1\left(x_{01}\frac{r}{R}\right) e^{j\omega t}$$

$m = 0$: rotation symmetry of the fields

$n = 1$: no zeros of the axial field component in $\vec{r}$

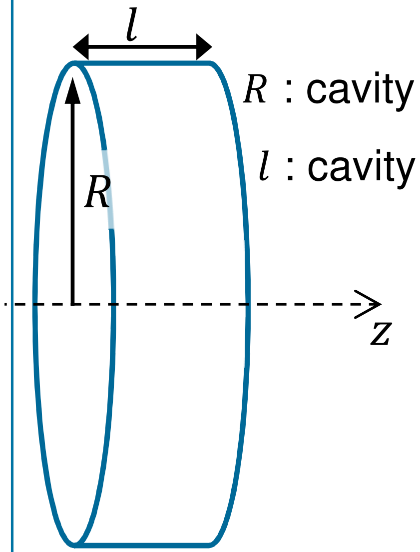
$p = 0$: no variation in z of the fields

J_m : Bessel´s functions

J'_m : derivative of the Bessel´s functions

angular frequency : $\omega = c\dfrac{x_{01}}{R}$ $\quad x_{01} = 2.405$

boundary conditions



R : cavity radius

l : cavity length

fundamental solution with $B_z = 0$ (that is, $\vec{B}$ is transverse)

$$E_z = E_0 J_0\left(x_{01}\frac{r}{R}\right) e^{j\omega t}$$

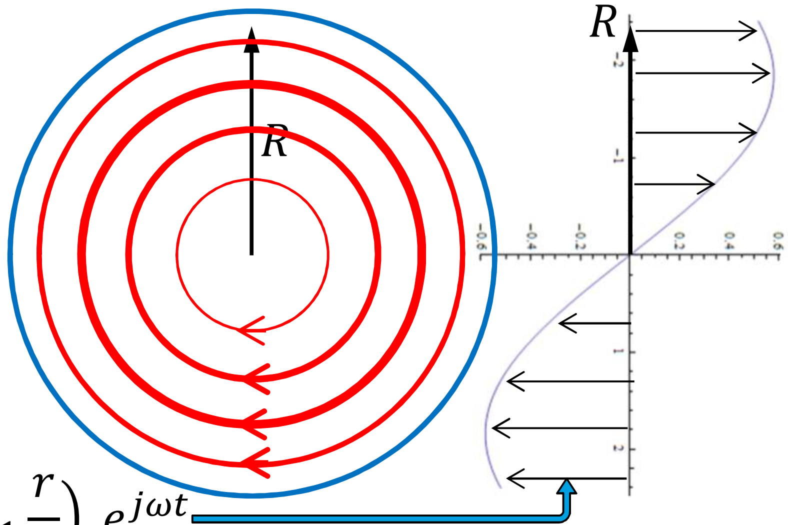
$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

$$B_\theta = j\omega \frac{R}{x_{01}c^2} E_0 J_1\left(x_{01}\frac{r}{R}\right) e^{j\omega t}$$



$m = 0$: rotation symmetry of the fields

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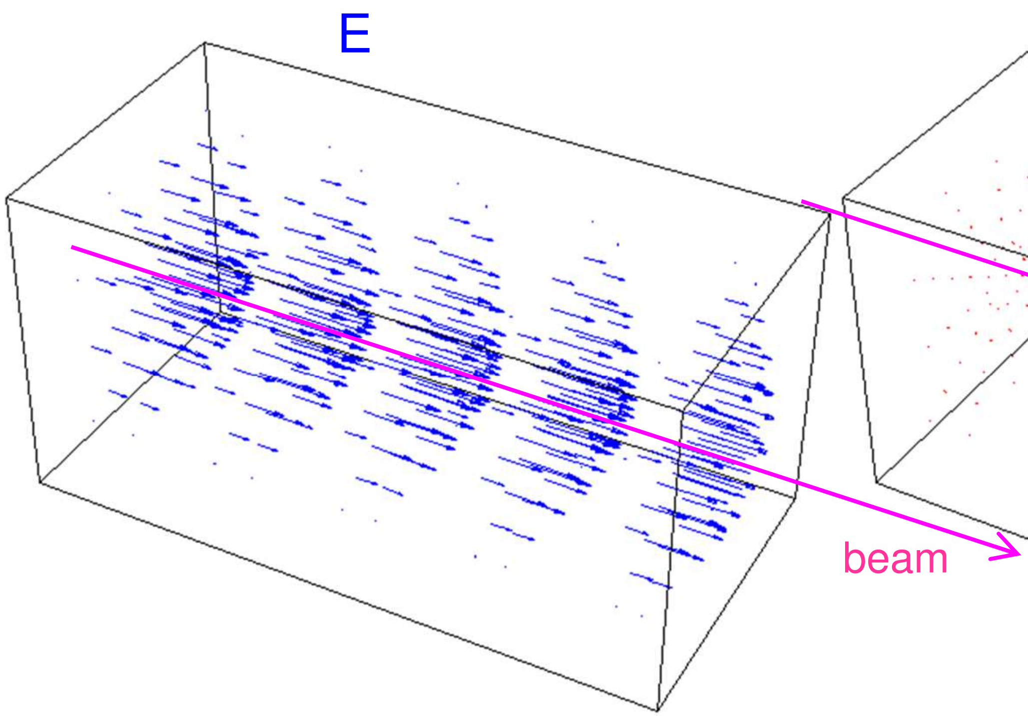
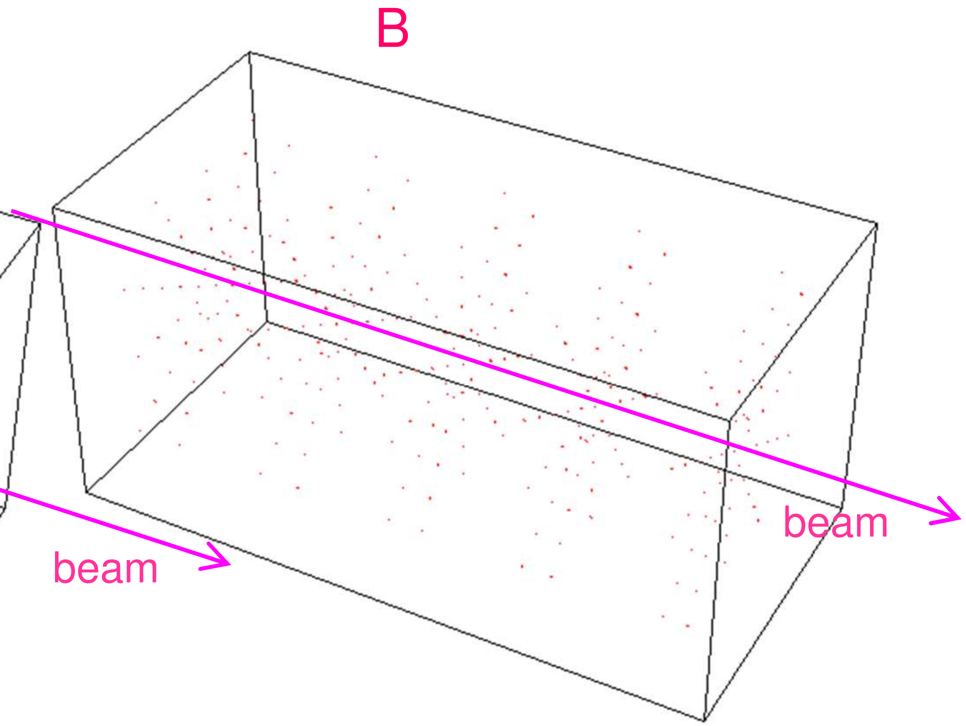
J'_m : derivative of the Bessel´s functions

angular frequency : $\omega = c\dfrac{x_{01}}{R}$ $\qquad x_{01} = 2.405$

Pill box cavity: 3D visualisation of E and B

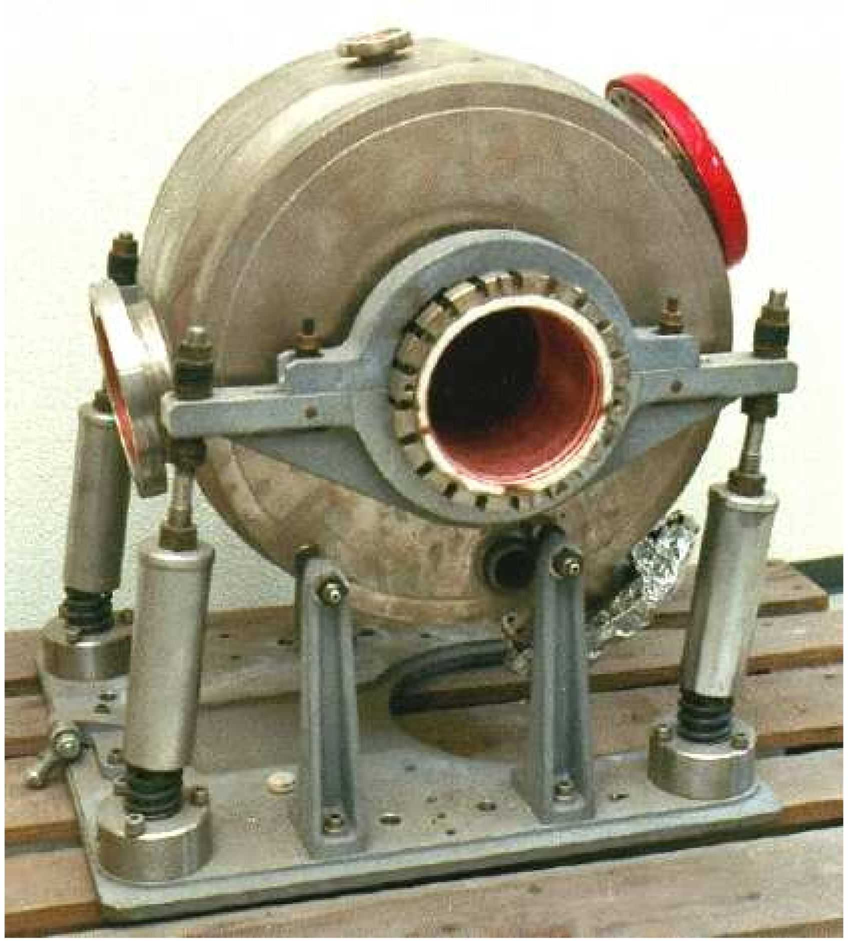




Equations for the electric and magnetic fields in a pill box cavity

Examples of pill box cavities

DESY cavity (pill box)

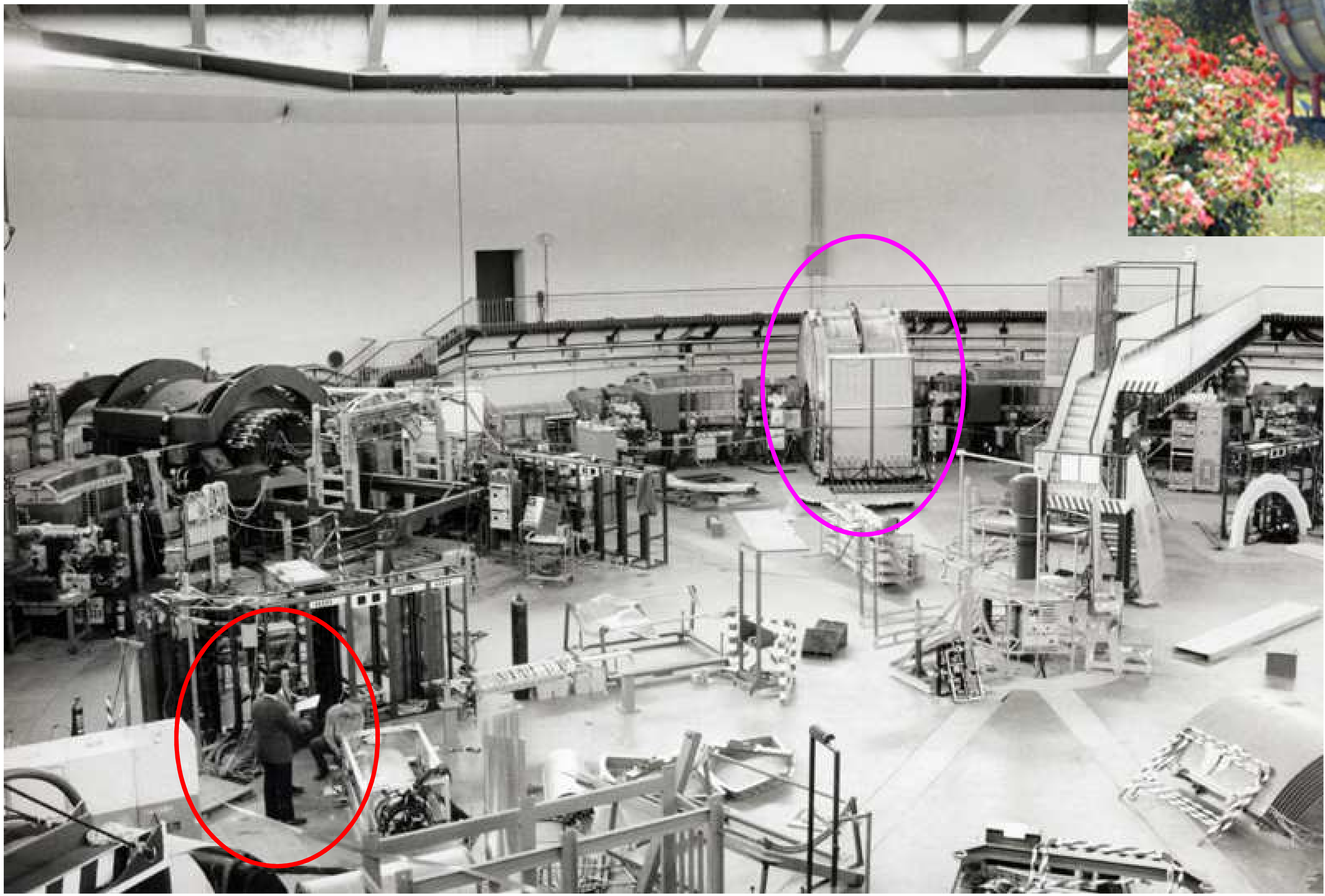


ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

Examples of pill box cavities

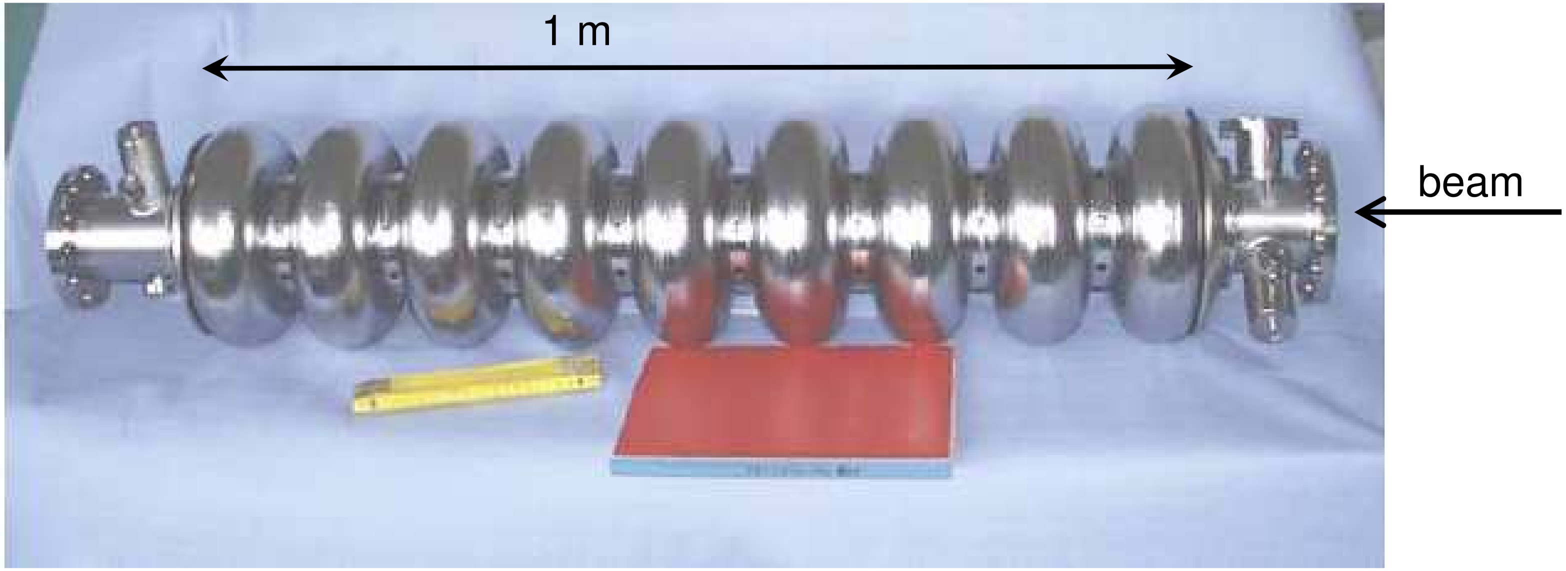
ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

ADONE in 1963, Laboratori Nazionali di Frascati, Italy



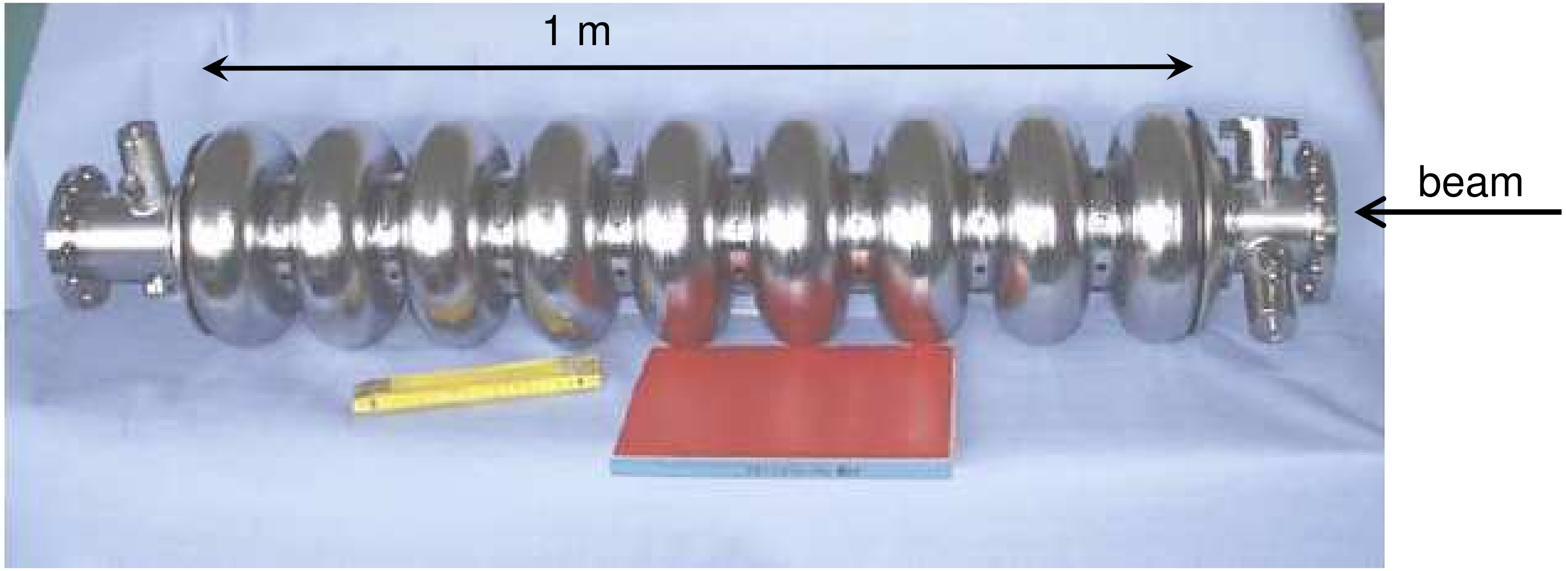
Superconducting cavity used at DESY

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)



Free-electron LASer in Hamburg	0.3 km	DESY	2004- ?	e-	1.2 GeV
European X-ray Free-Electron Laser	3 km	DESY	2016- ?	e-	17.5 GeV
International Linear Collider	30 km	?	?	e-/e+	2x250 GeV

Superconducting cavity used at DESY

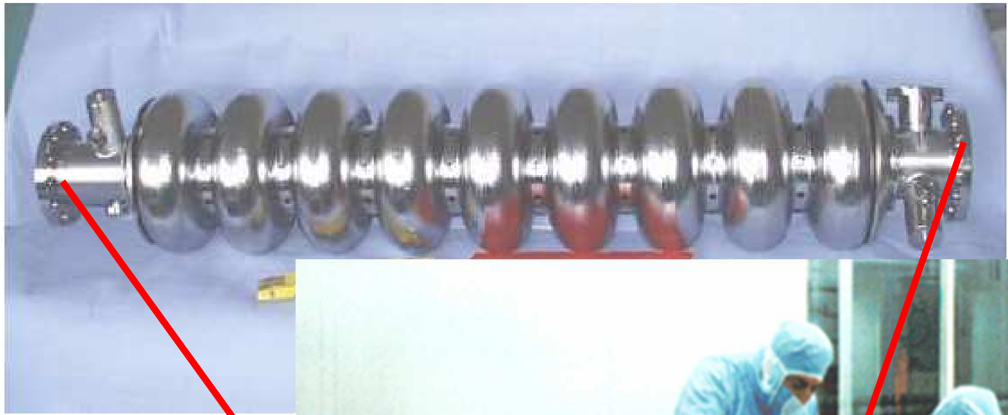


material: pure Niobium

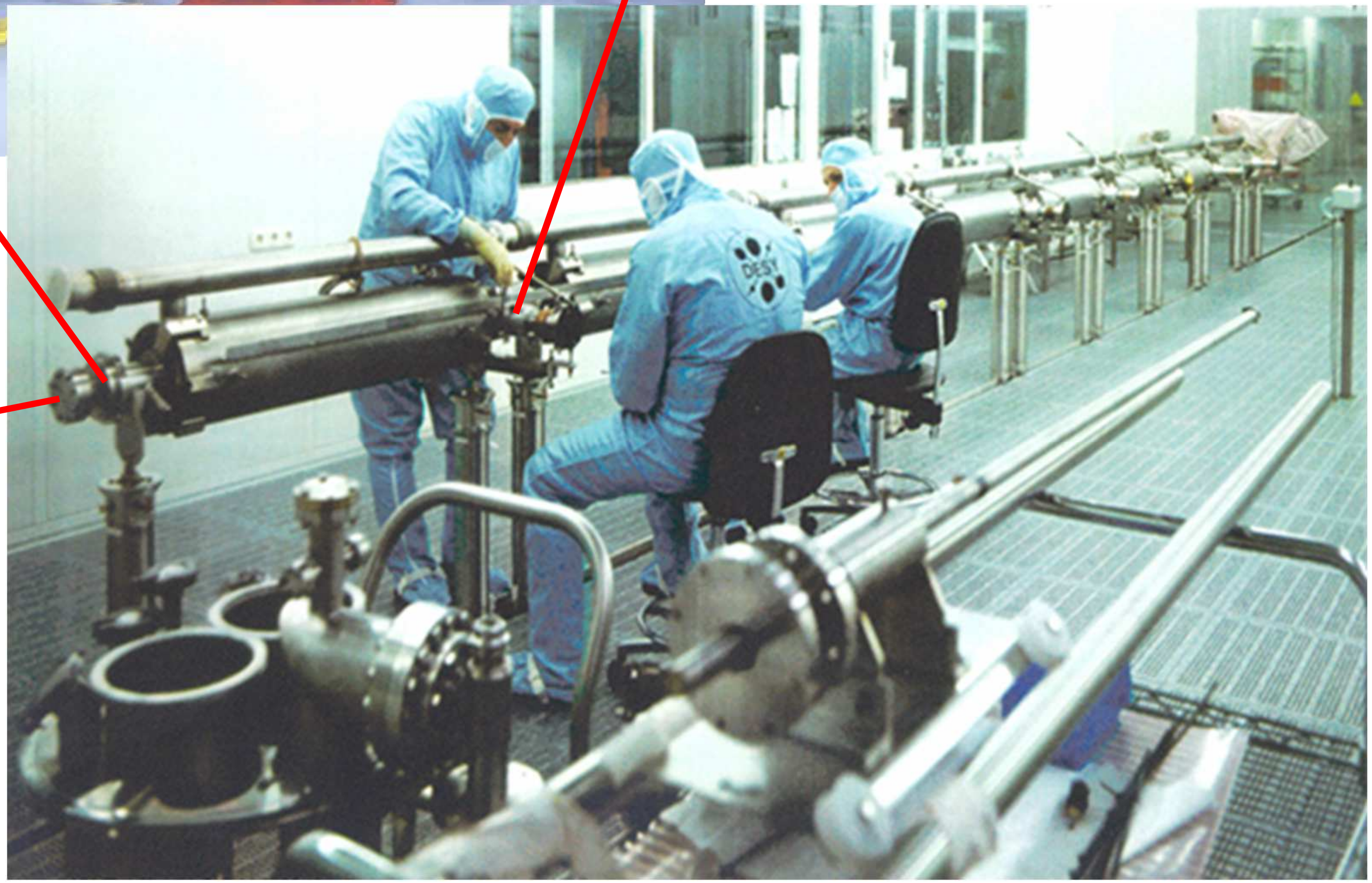
operating temperature: 2 K

accelerating field gradient: up to 35 MV/m

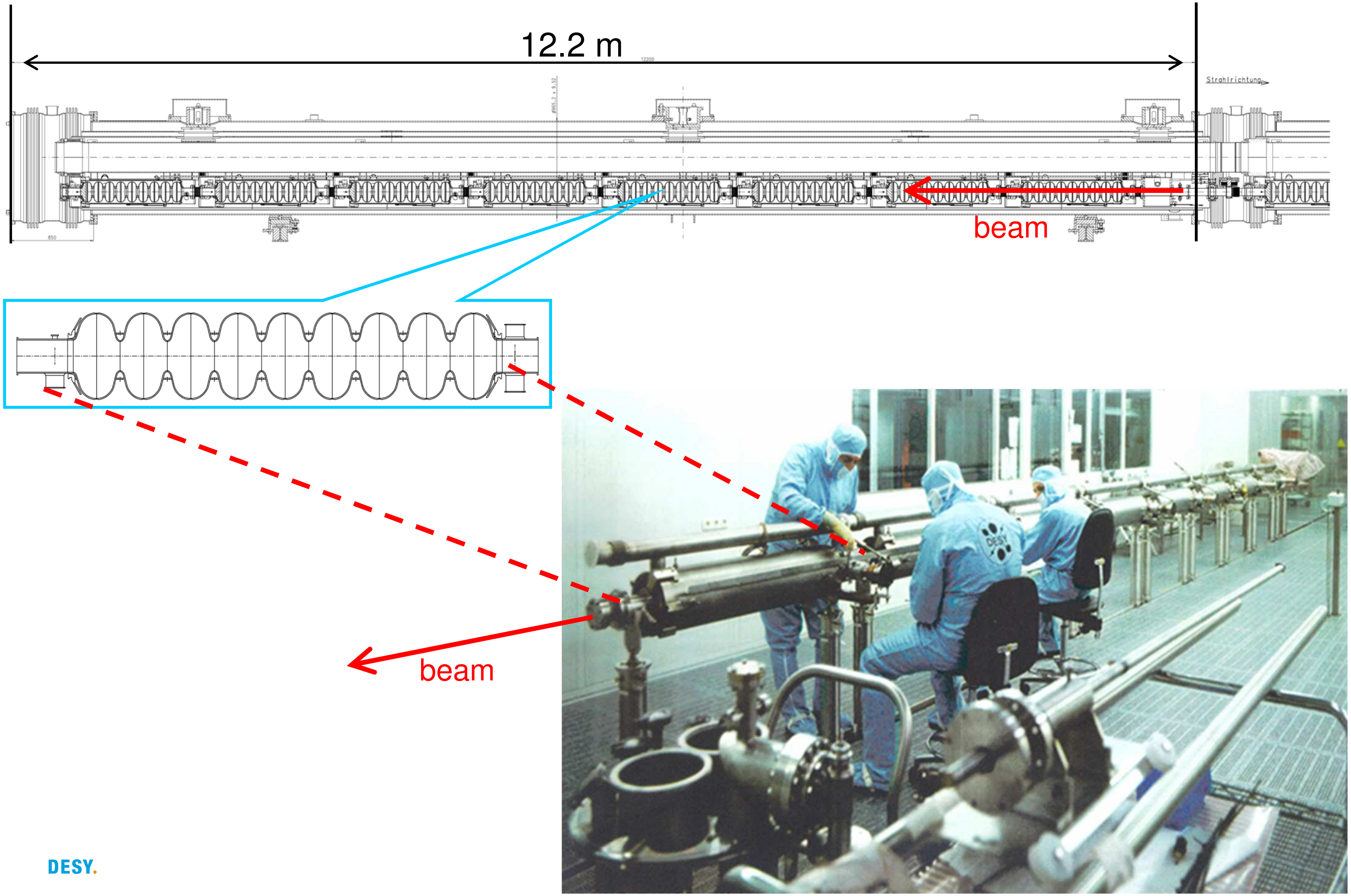
Cavities inside a cryostat



Number of cavities	8
Cavity length	1.038 m
Operating frequency	1.3 GHz
Operating temperature	2 K
Accelerating Gradient	23..35 MV/m



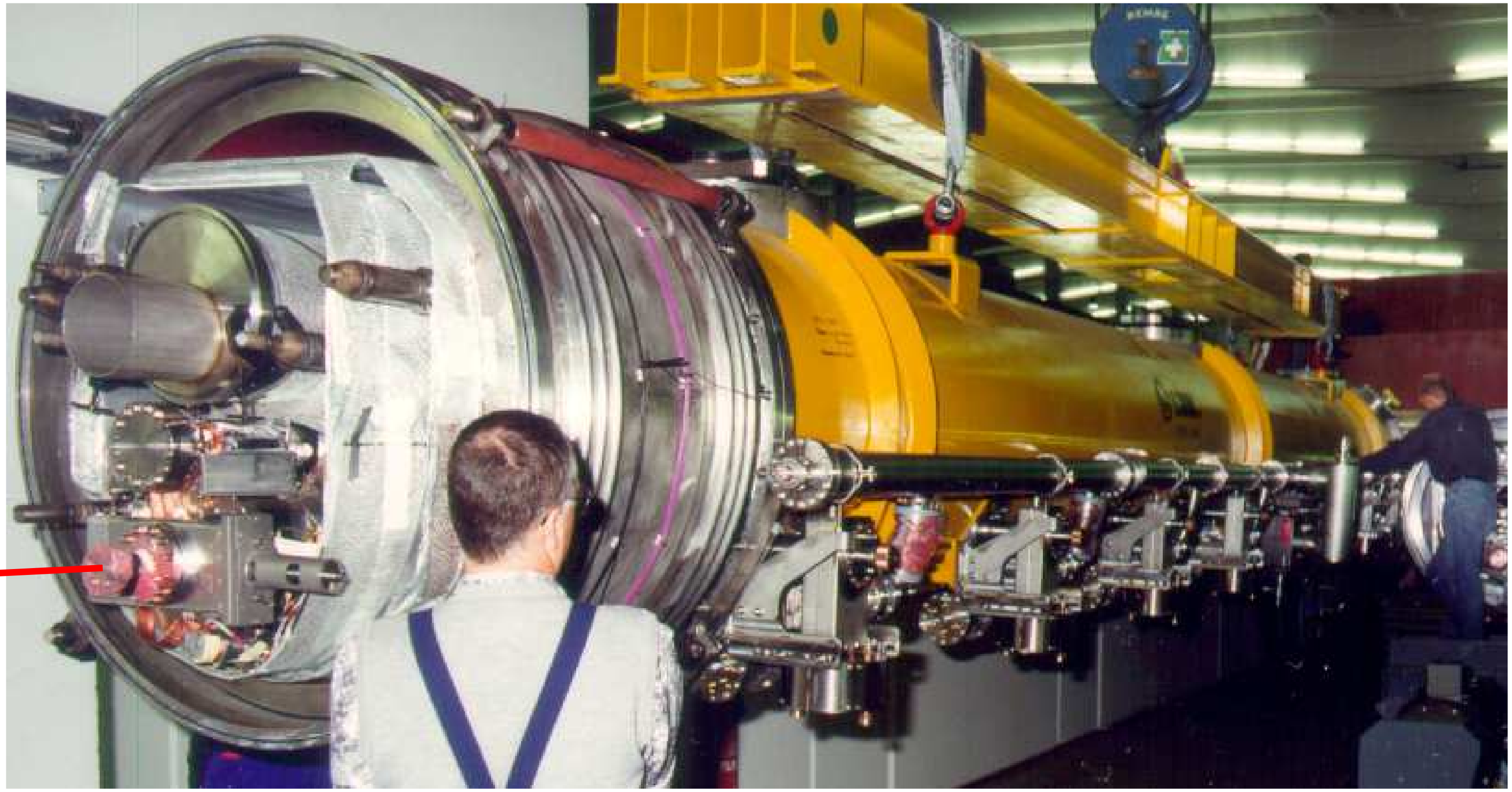
beam


12.2 m
12200
Strahlrichtung
850
beam
beam

Cavities inside a cryostat

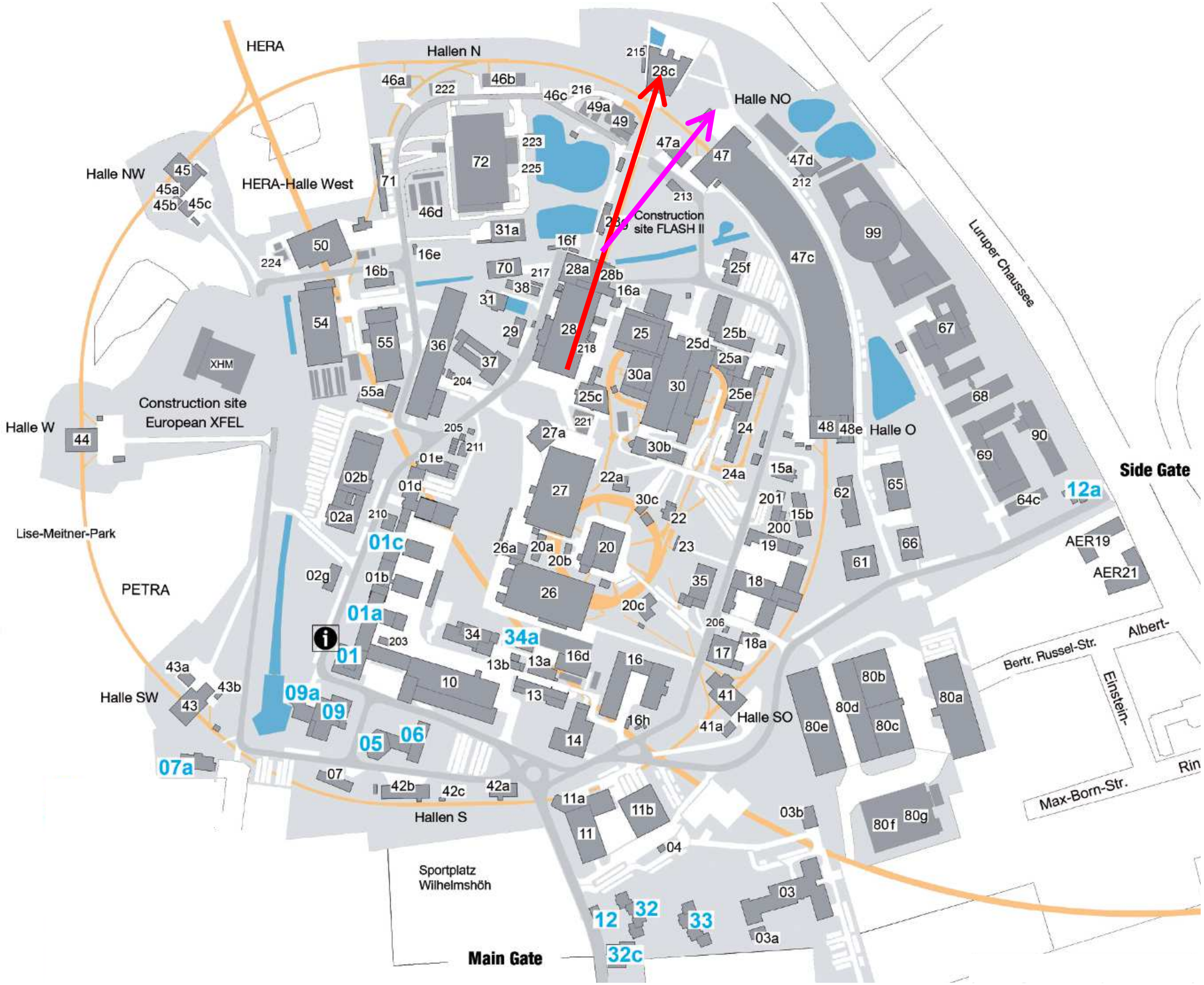
Cavities inside an accelerator module (cryostat)

beam

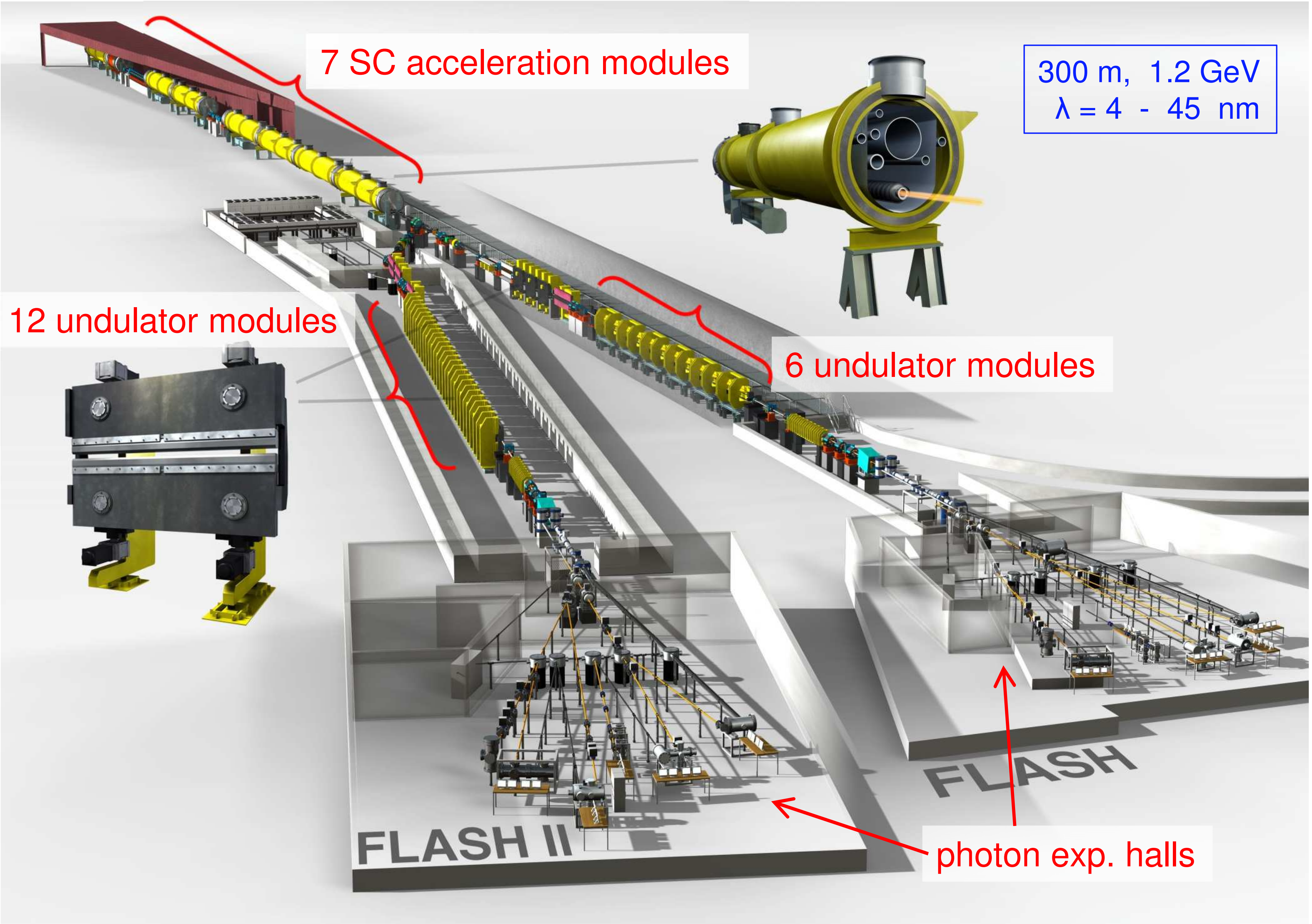


module installation in FLASH (2004)

Free-electron LASer in Hamburg (FLASH)



Free-electron LASer in Hamburg (FLASH)

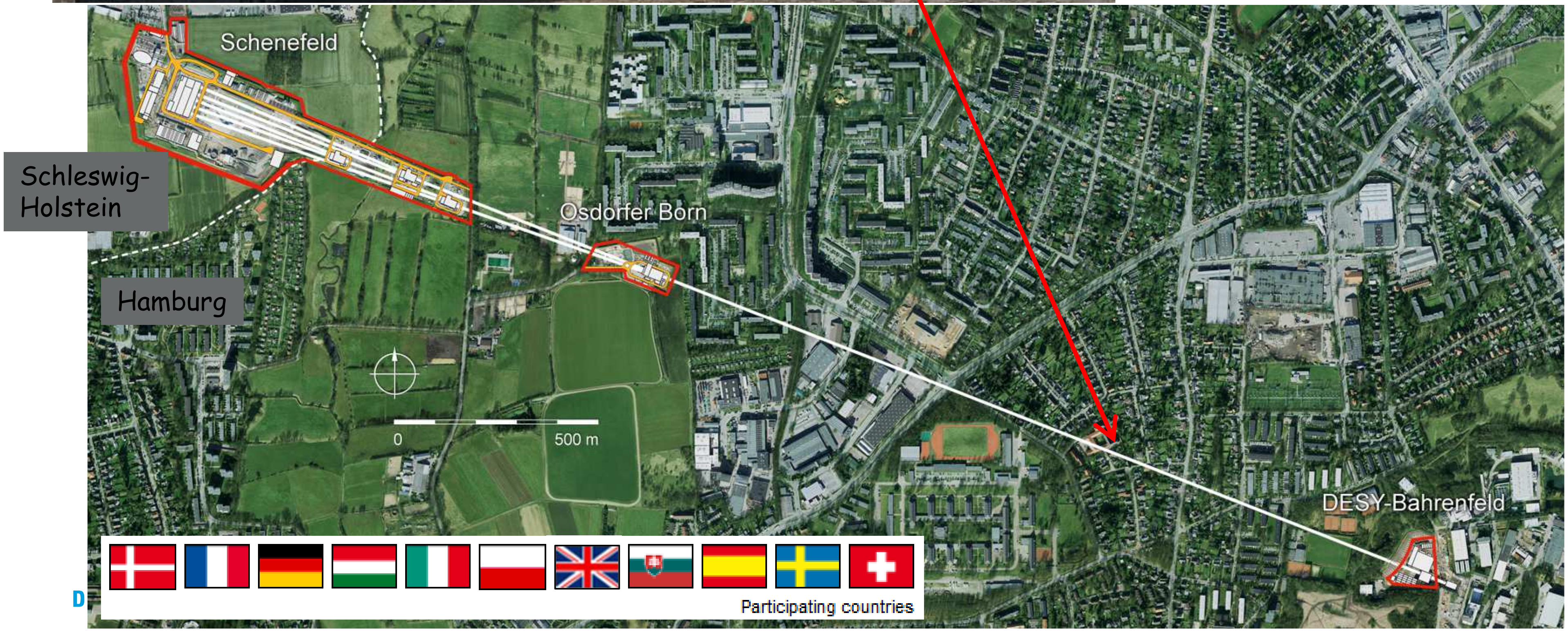


100 accelerator modules (cryostats) in XFEL

European X-ray Free-Electron Laser (XFEL)

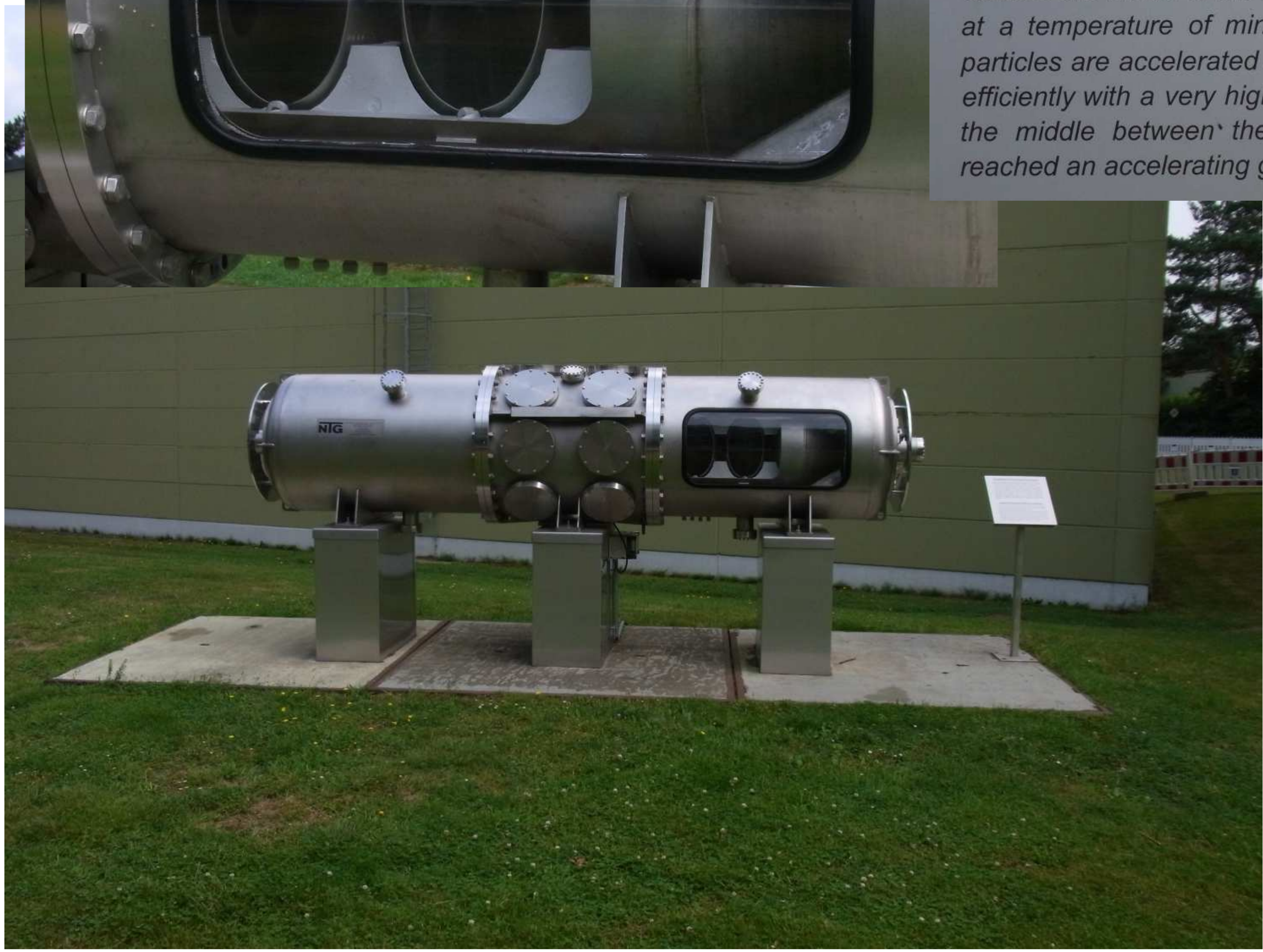
(3 km, 17.5 GeV)

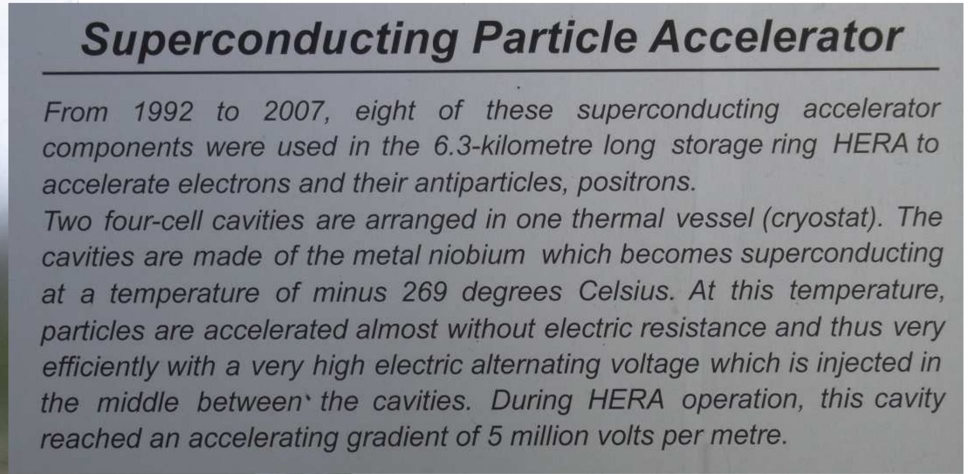
$\boxed{\lambda = 0.05 \ - \ 6 \ \text{nm}}$



Superconducting cavities at HERA

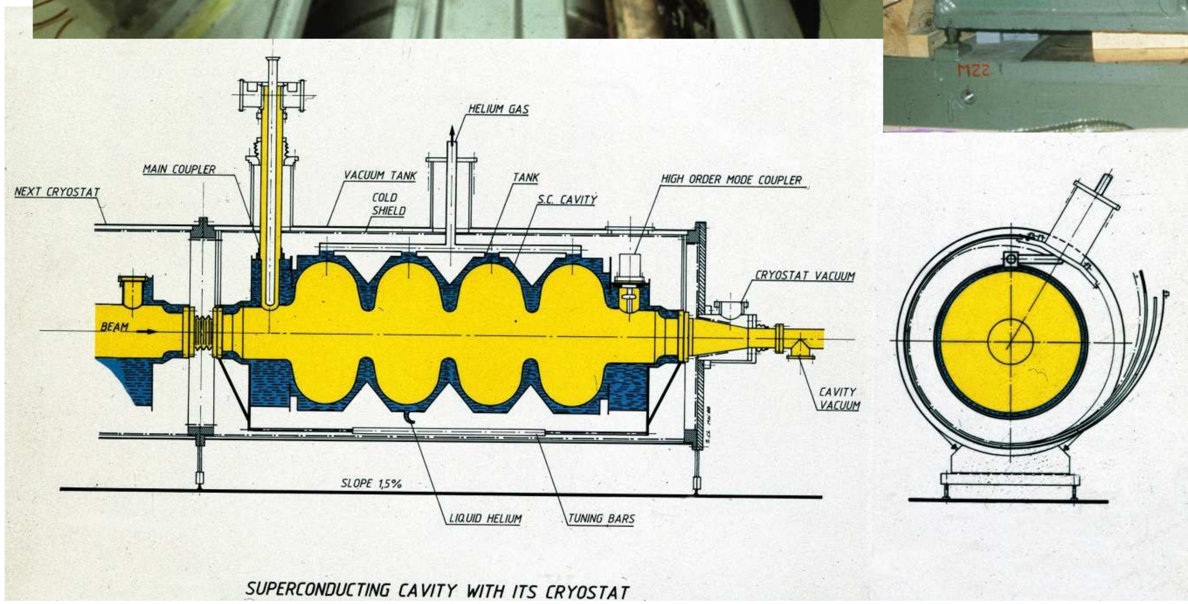
16 cavities
500 MHz





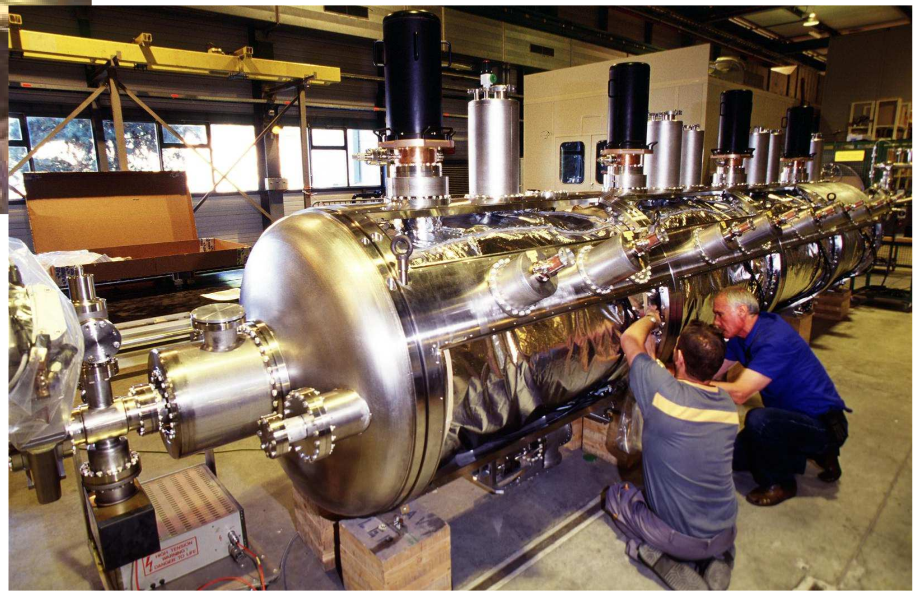
Superconducting cavities at LEP

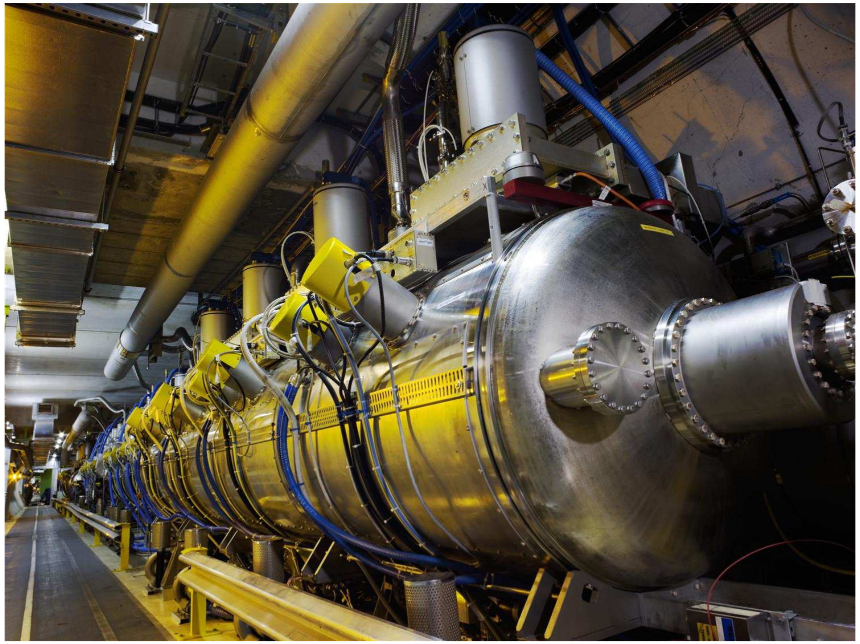
272 cavities
352 MHz



Superconducting cavities at LHC

16 cavities
400 MHz





Other accelerators using superconducting cavities

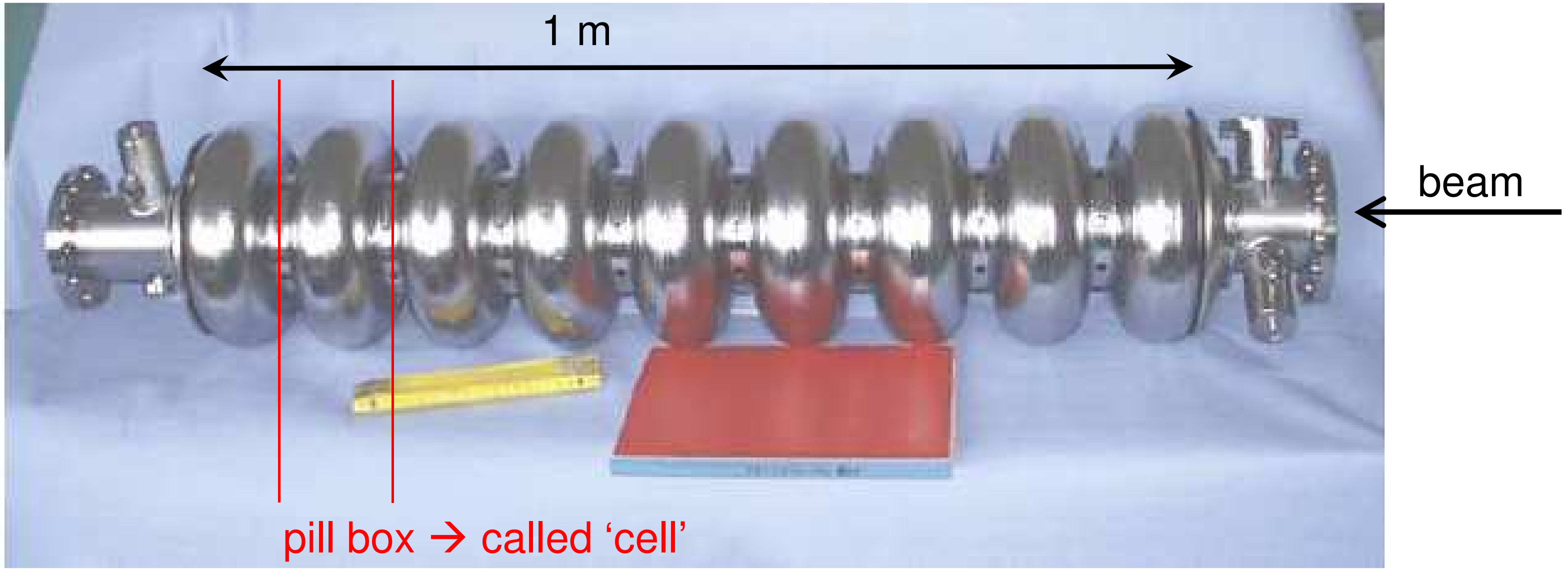
- 5 de-commissioned
- 11 in operation
- 4 in construction
- 10 in design phase

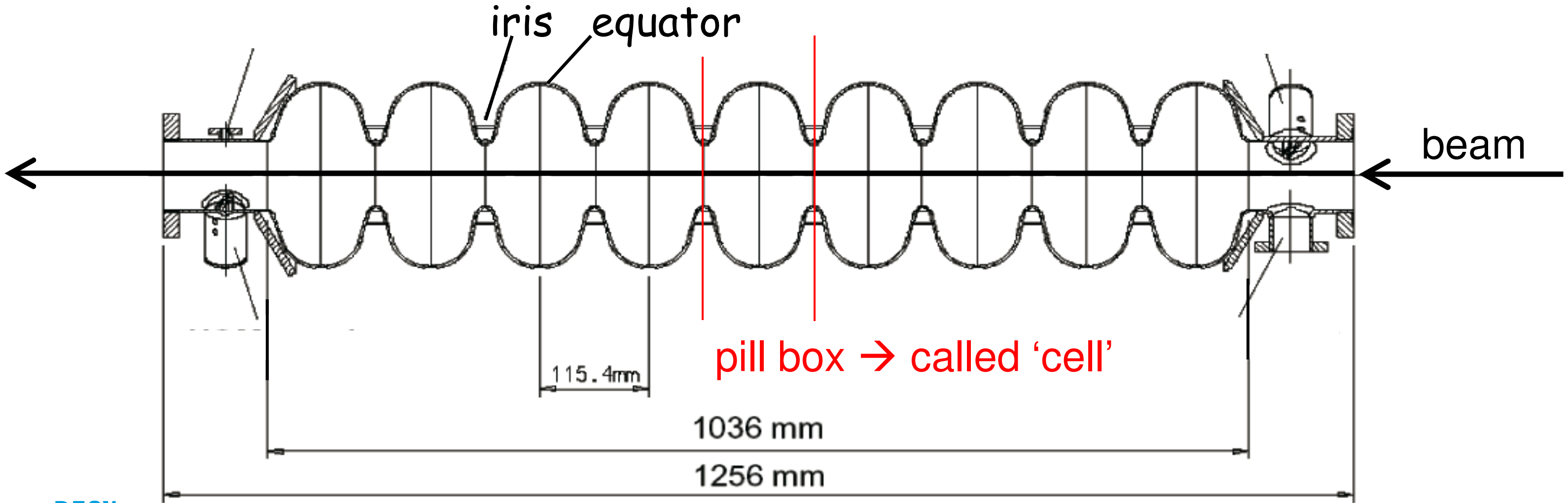
Total = 30

full list: http://tesla-new.desy.de/srf_accelerators

Superconducting cavity used in FLASH and in XFEL

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)



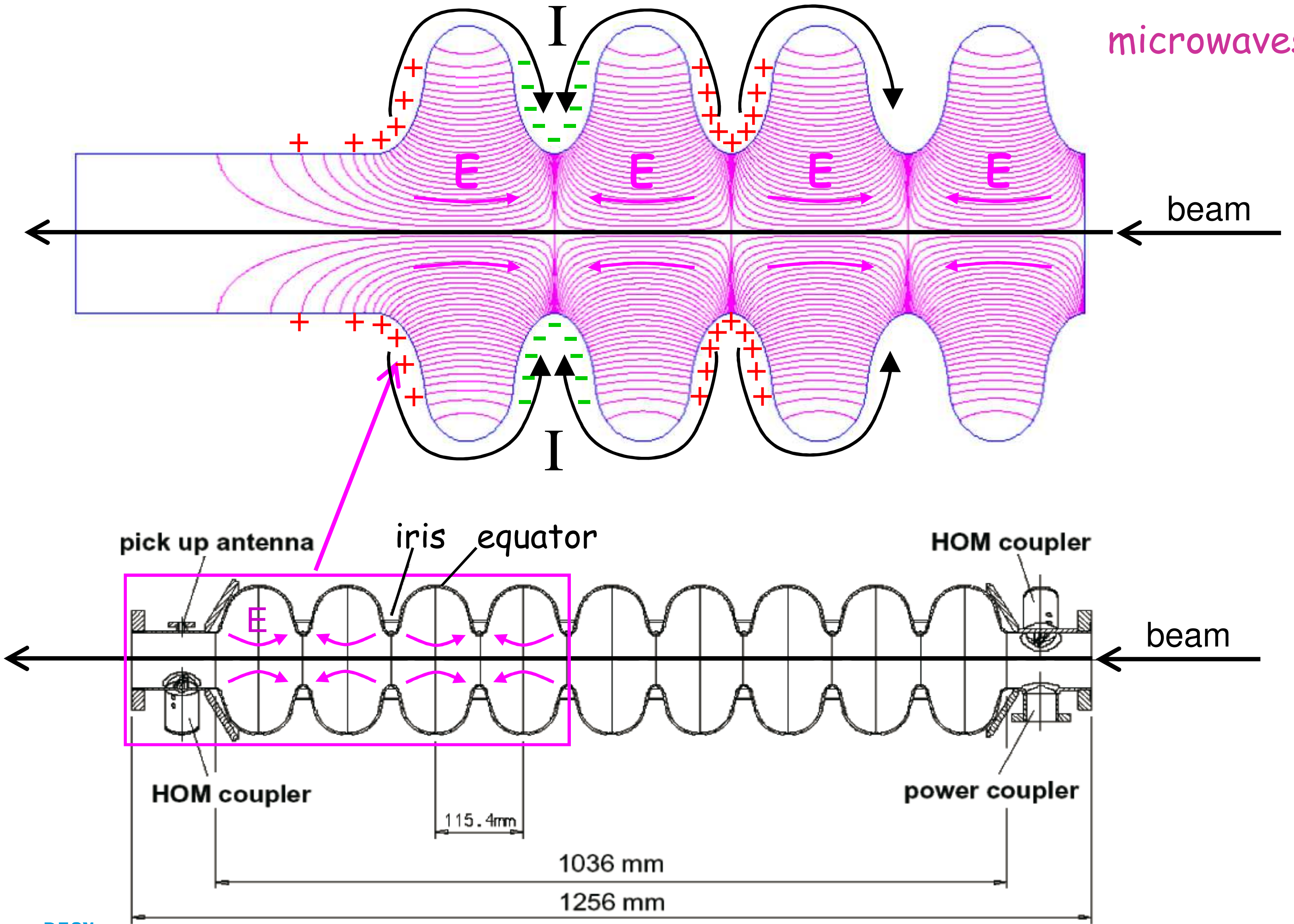


Accelerating field map

Simulation of the fundamental mode: electric field lines

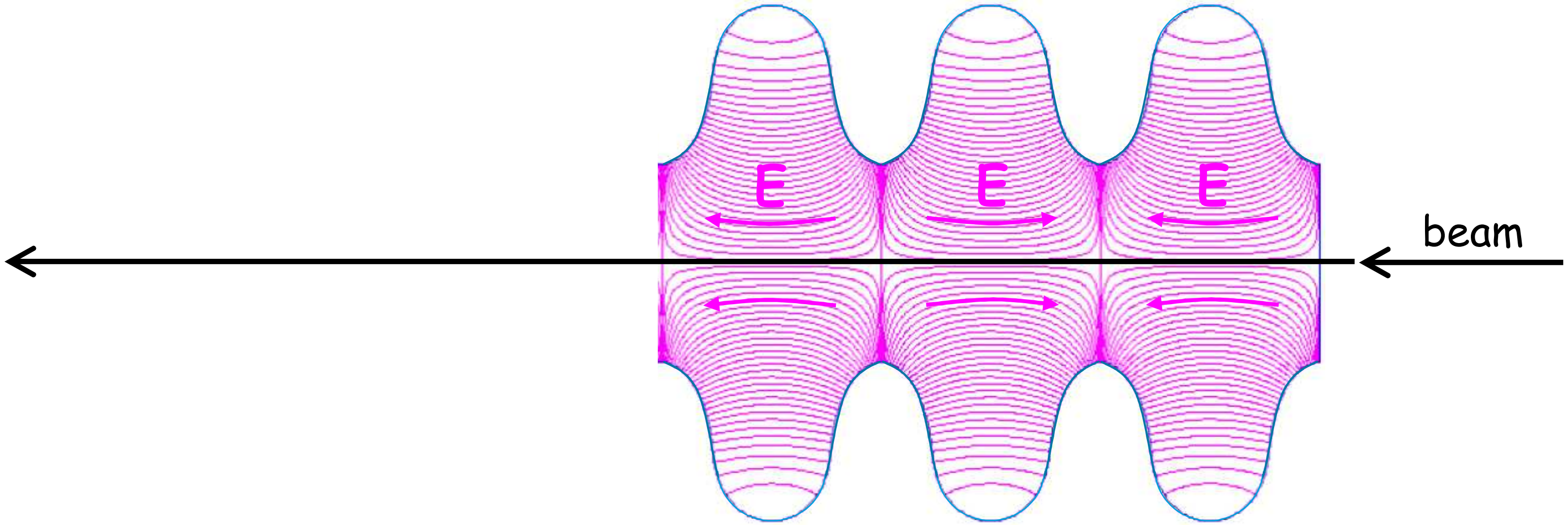
$f_{RF} = 1.3\ \text{GHz}$

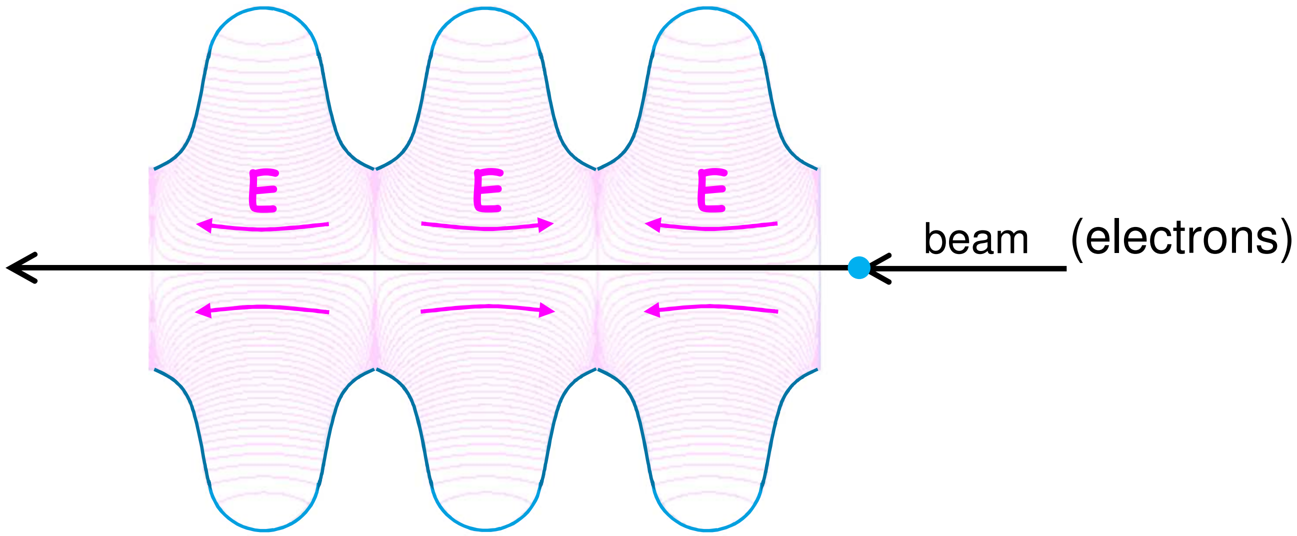
microwaves: (L-band)

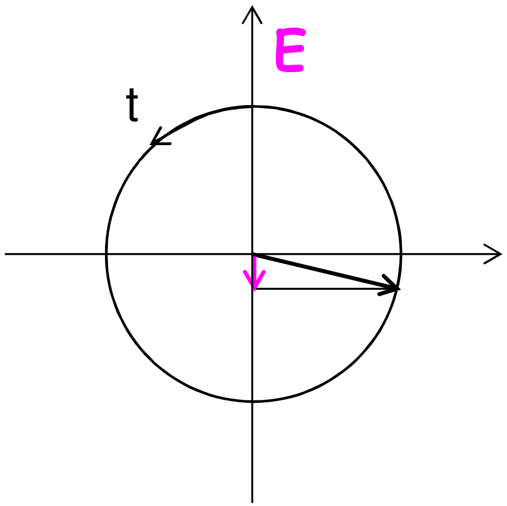


Is there a net acceleration?

Simulation of the fundamental mode: electric field lines




E
E
E
beam (electrons)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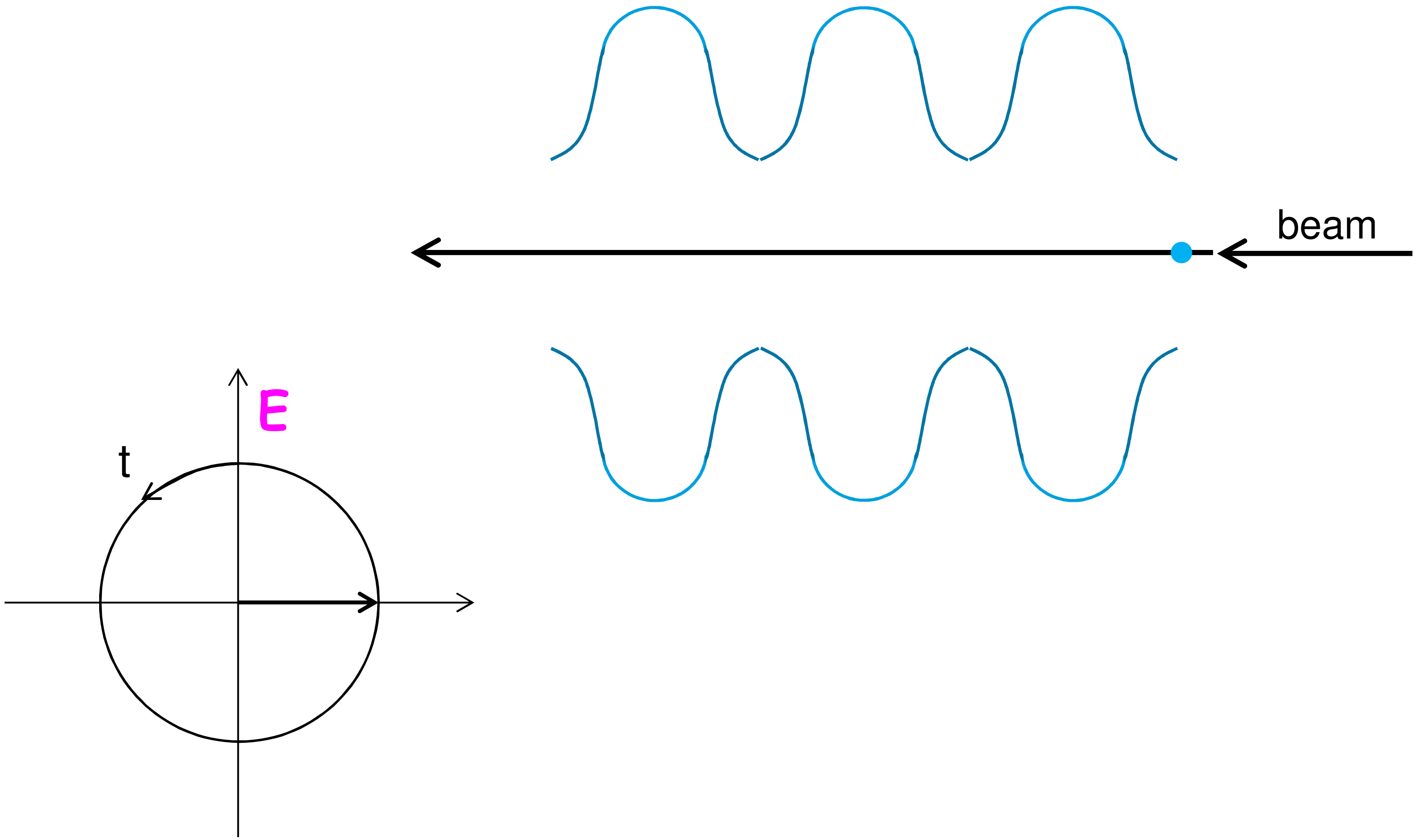
t


beam
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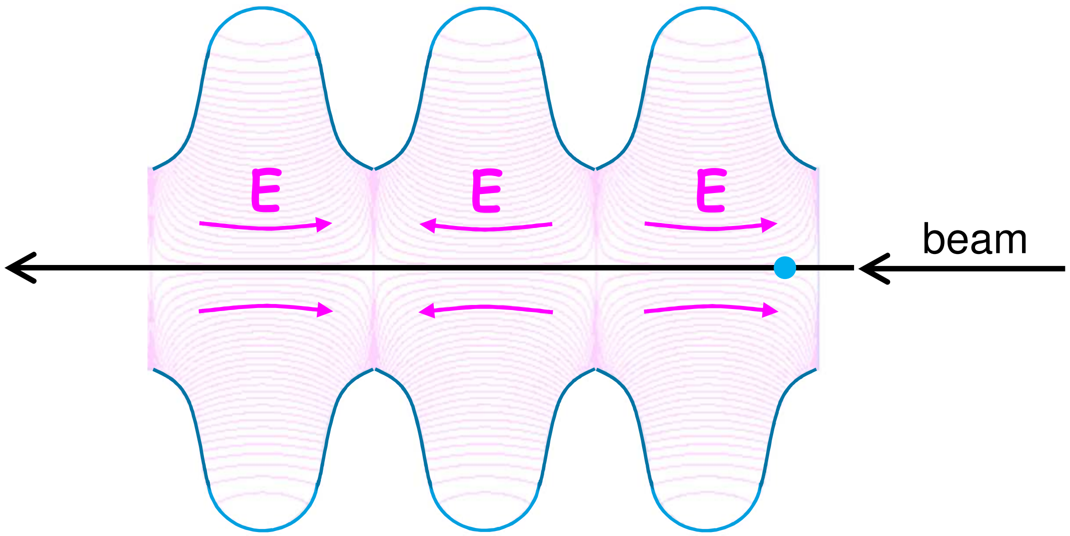
E
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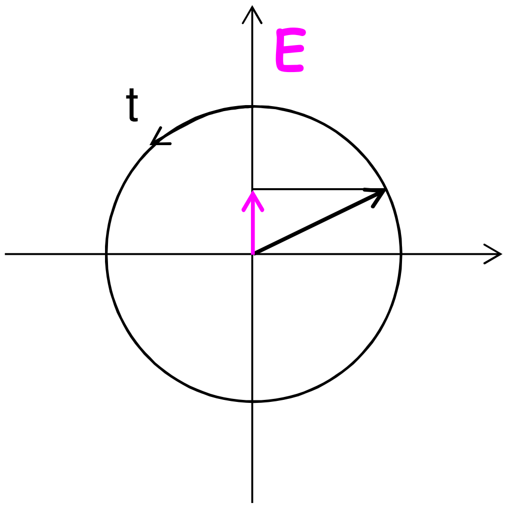
beam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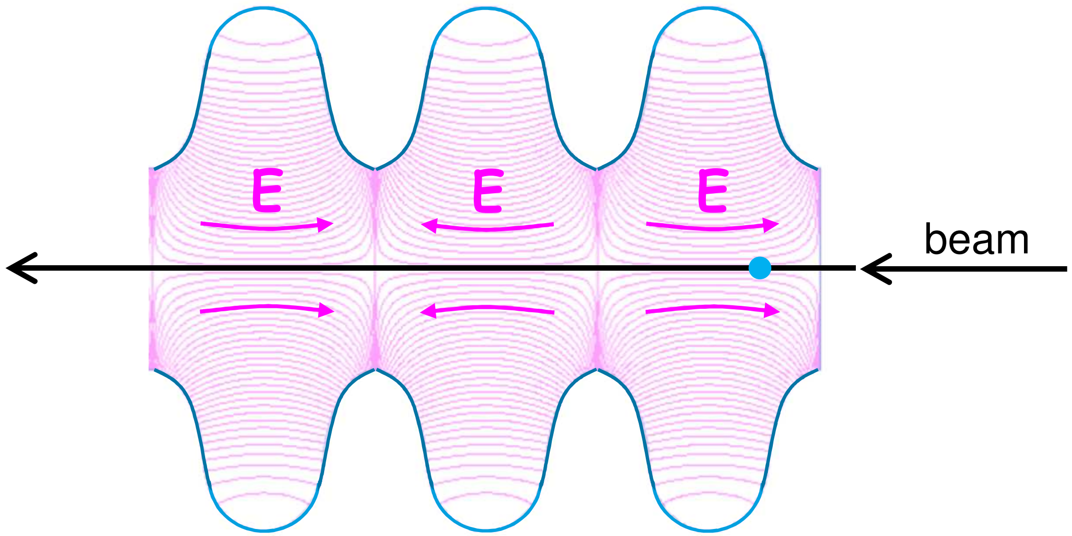
E
E
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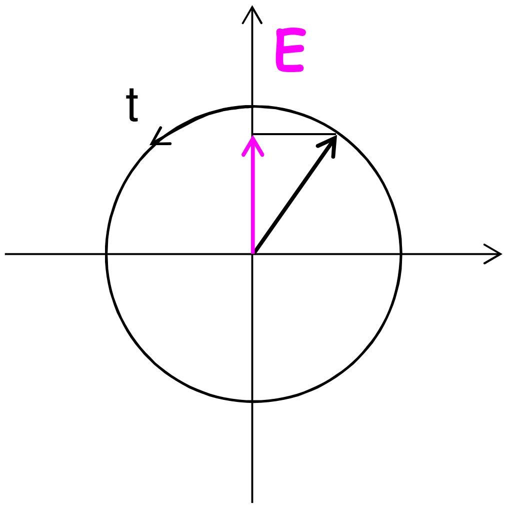
beam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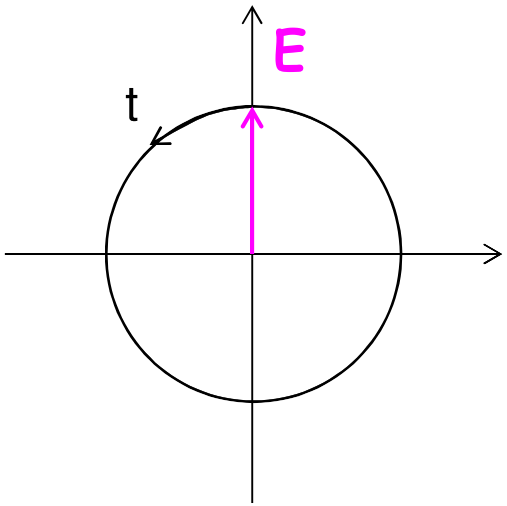
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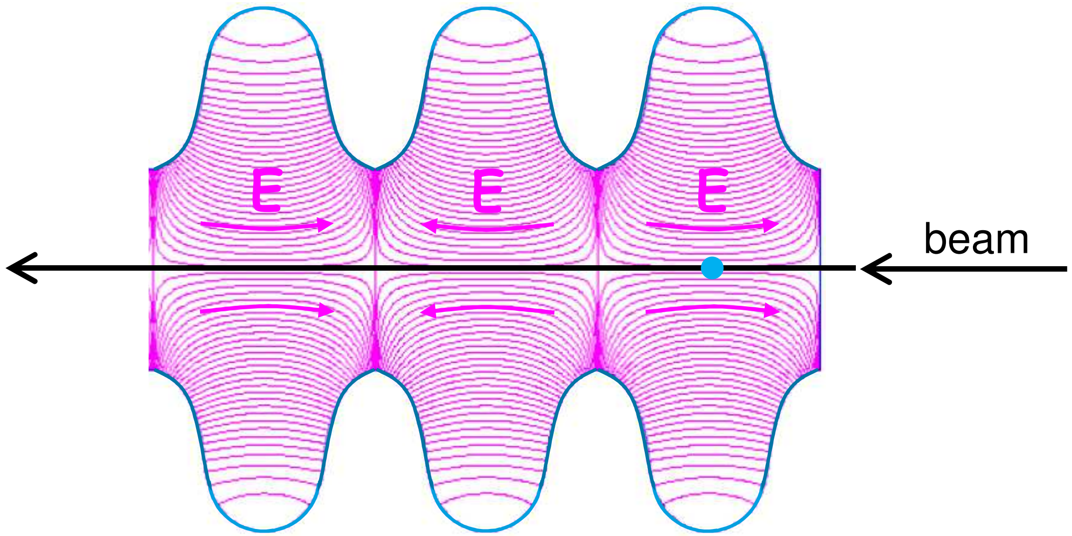
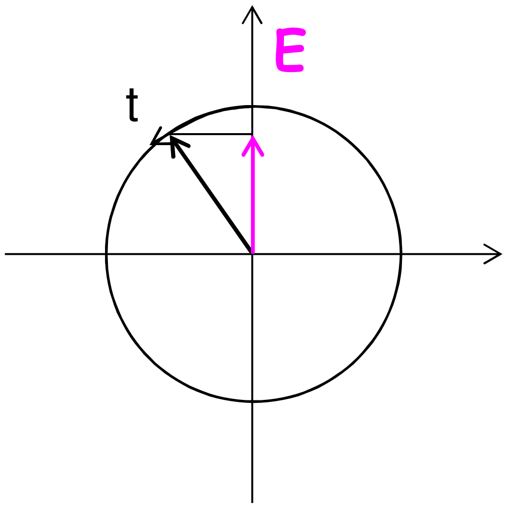

E
E
E
beam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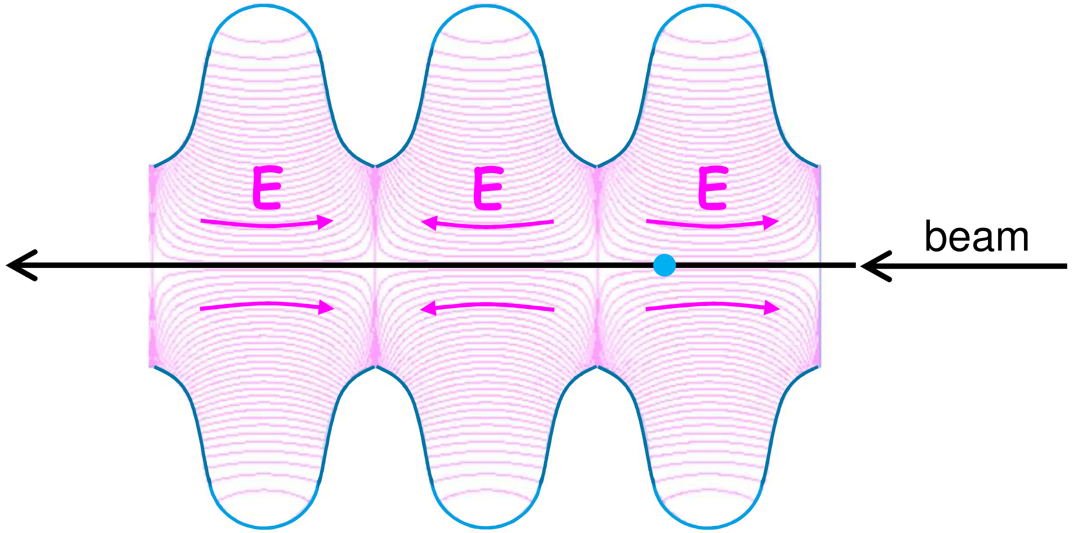
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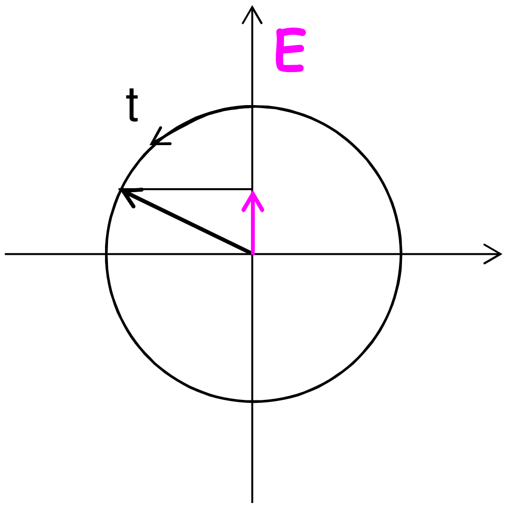
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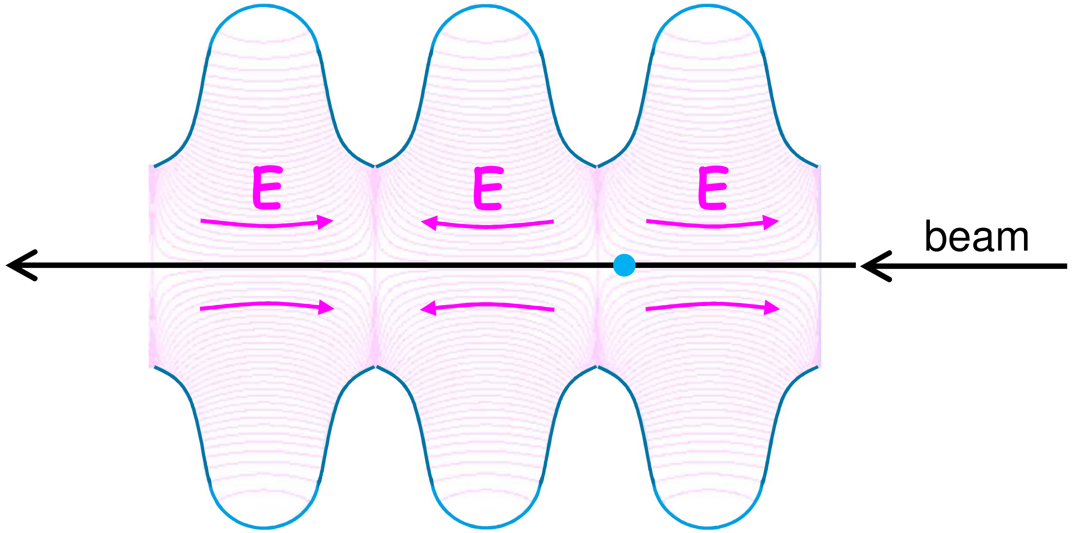
E
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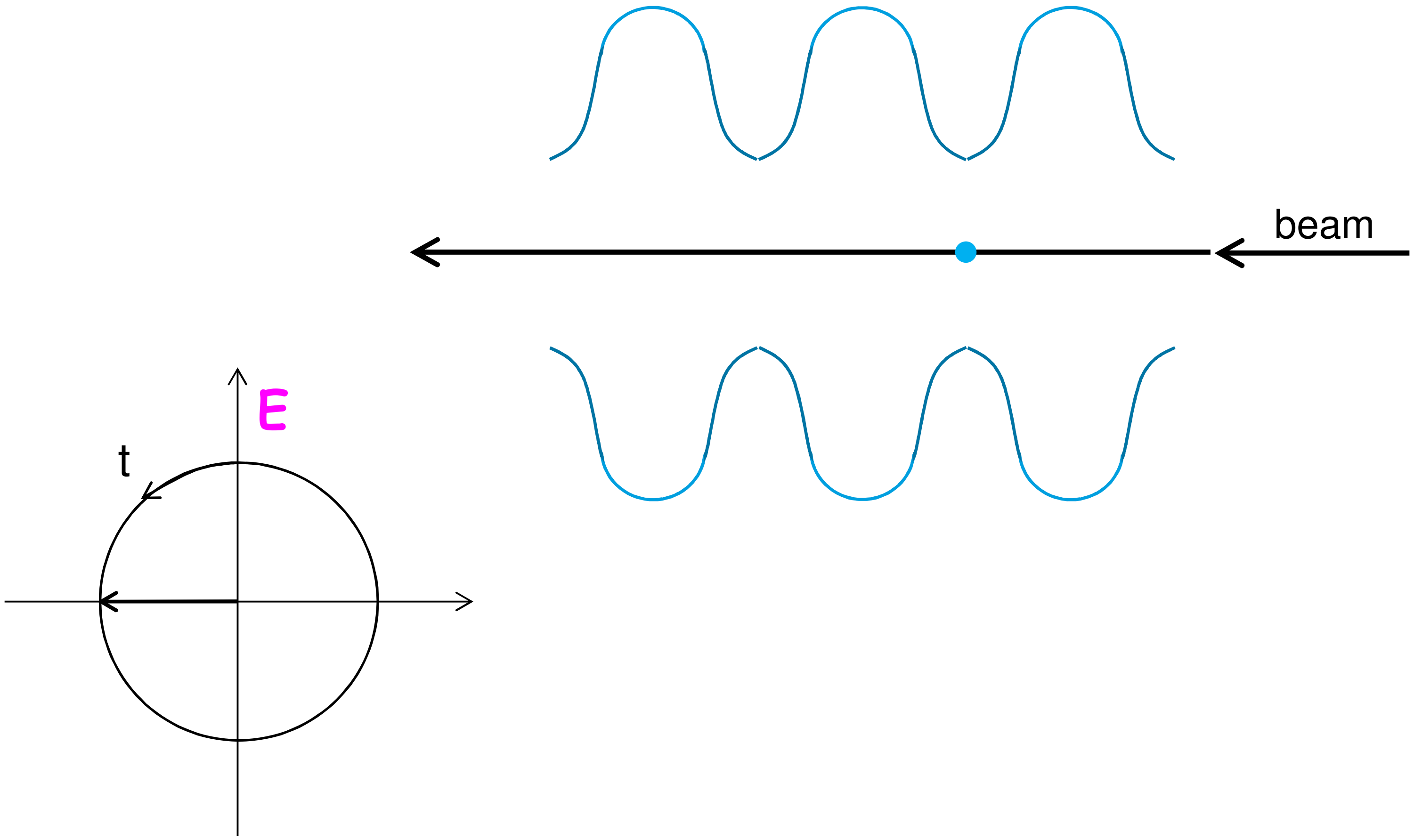
beam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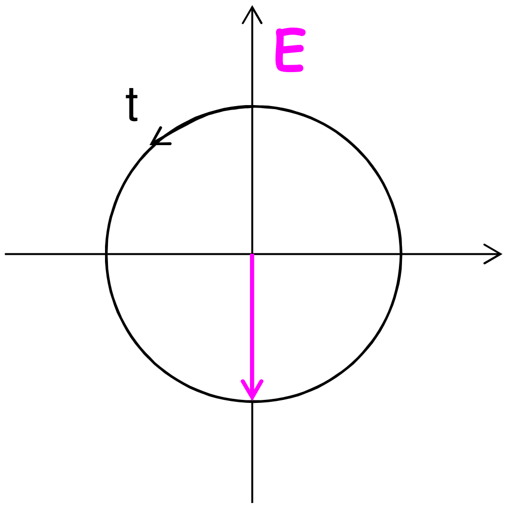
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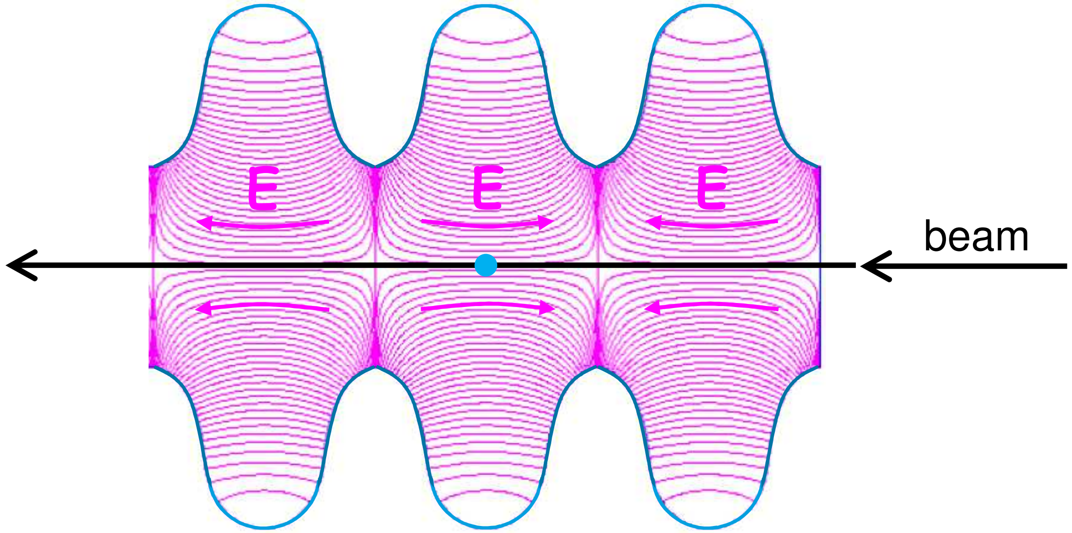
E
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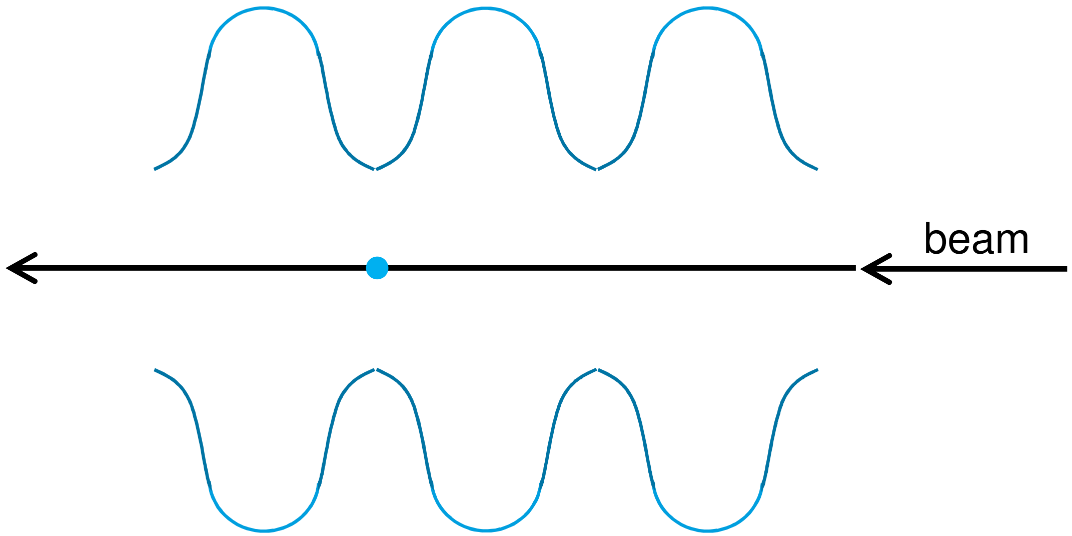
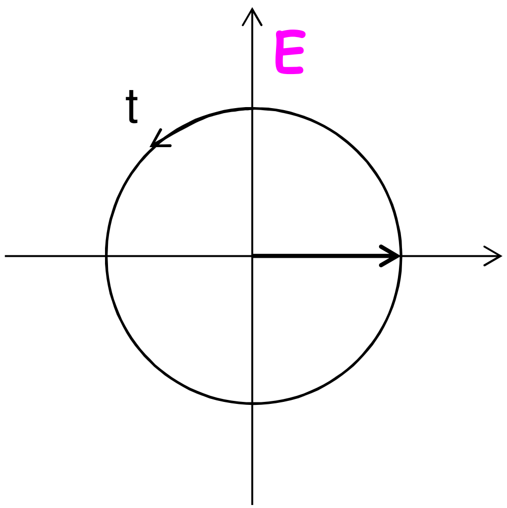
beam


beam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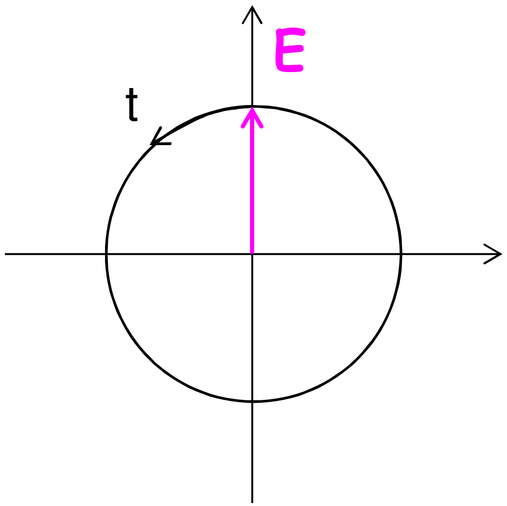
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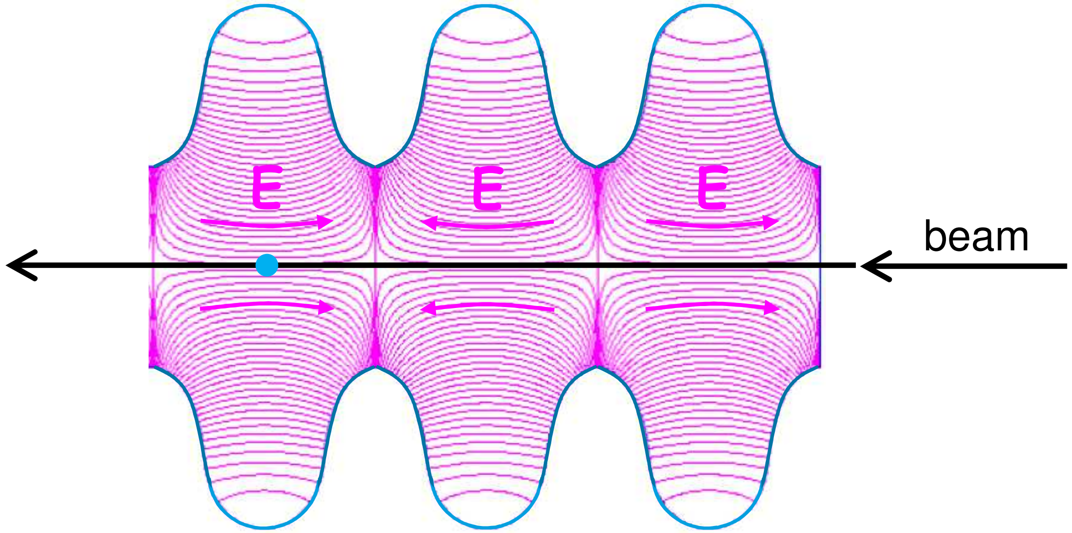
E
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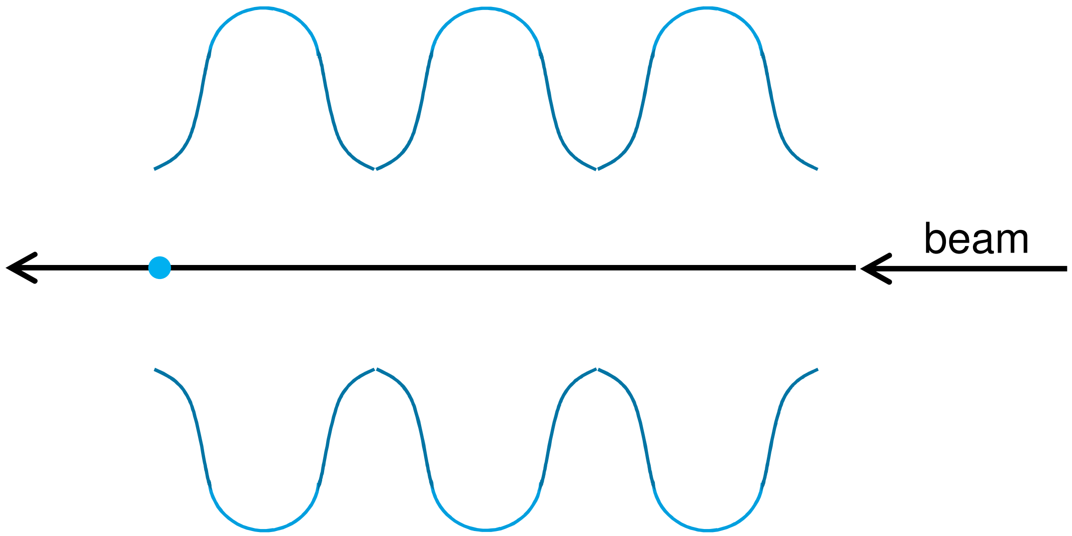
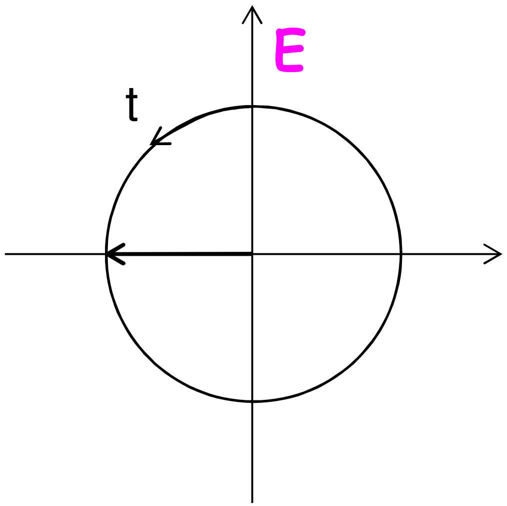
beam

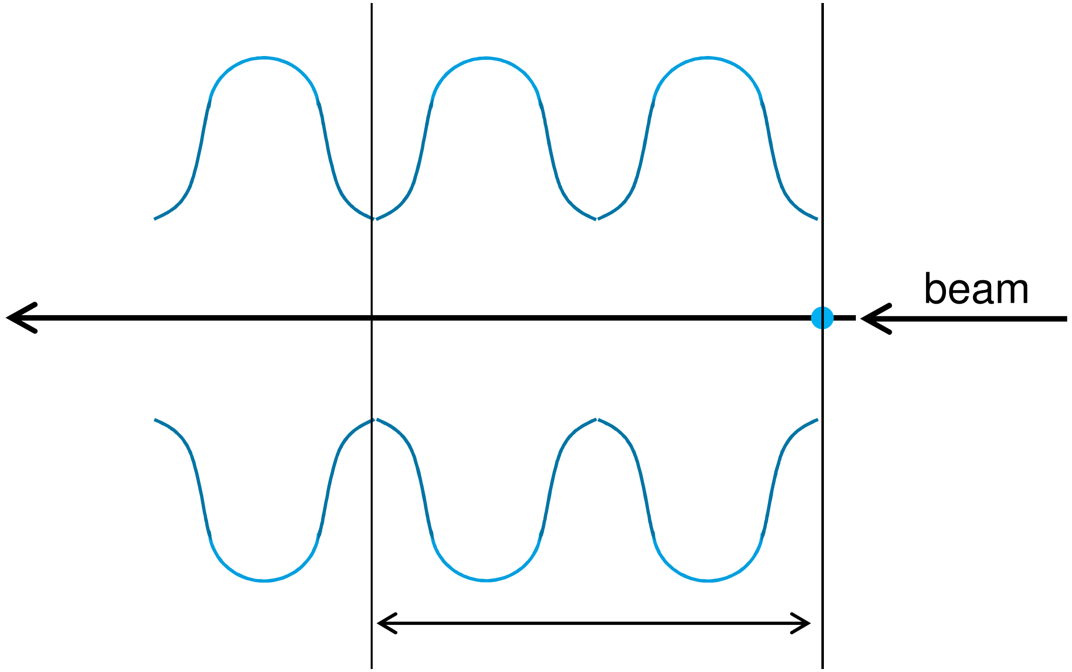

beam


E
t

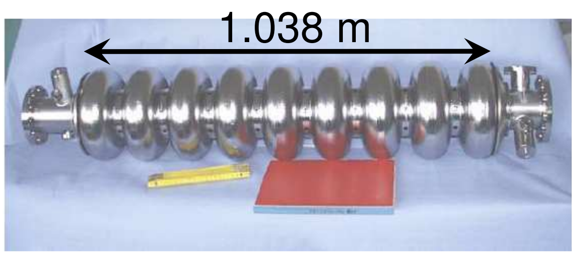
Is there a net acceleration? ……………………………… timing is the key

Is there a net acceleration? ……………………………… timing is the key

for electrons, $\beta \cong 1$



$$l = cT = \frac{c}{f} = \frac{3 \cdot 10^8}{1.3 \cdot 10^9} = 0.23\ m \quad \text{(2 cells)}$$

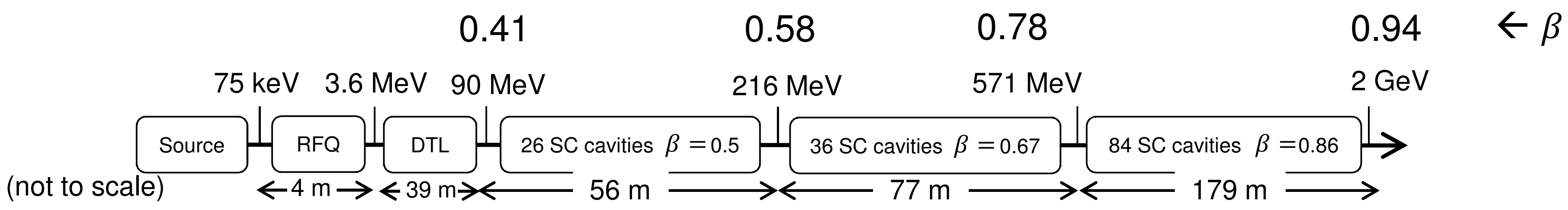


1 cavity (1.038 m) / 9 cells = 0.115 m

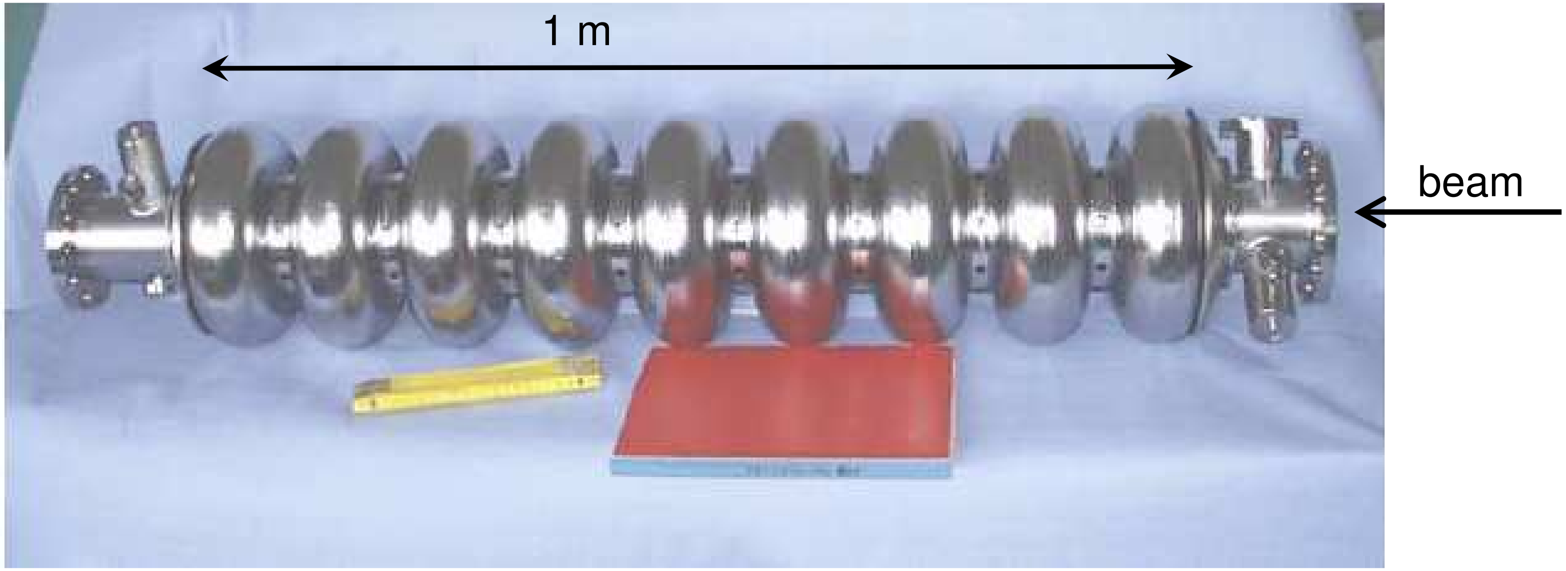
Is there a net acceleration? ……………………………… timing is the key

for protrons, $\beta < 1$

example: ESS (European Spallation Source), Lund, Sweden



Superconducting cavity used at DESY



Frequently Asked Questions

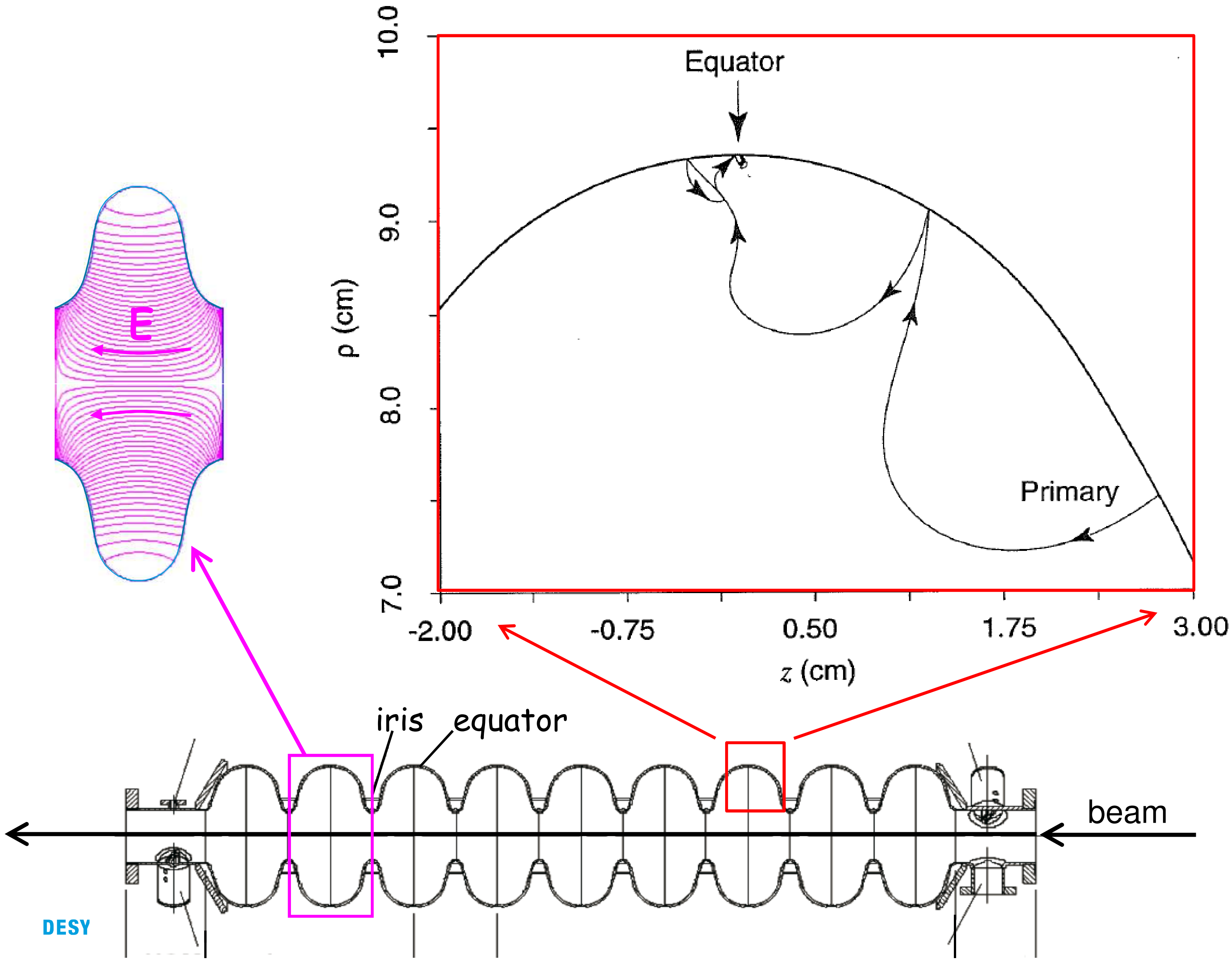
1) Why this shape?

2)

3)

4)

Multipacting mitigation in superconducting cavities



1) Why this shape? …………………………………………………… to reduce/avoid multipacting

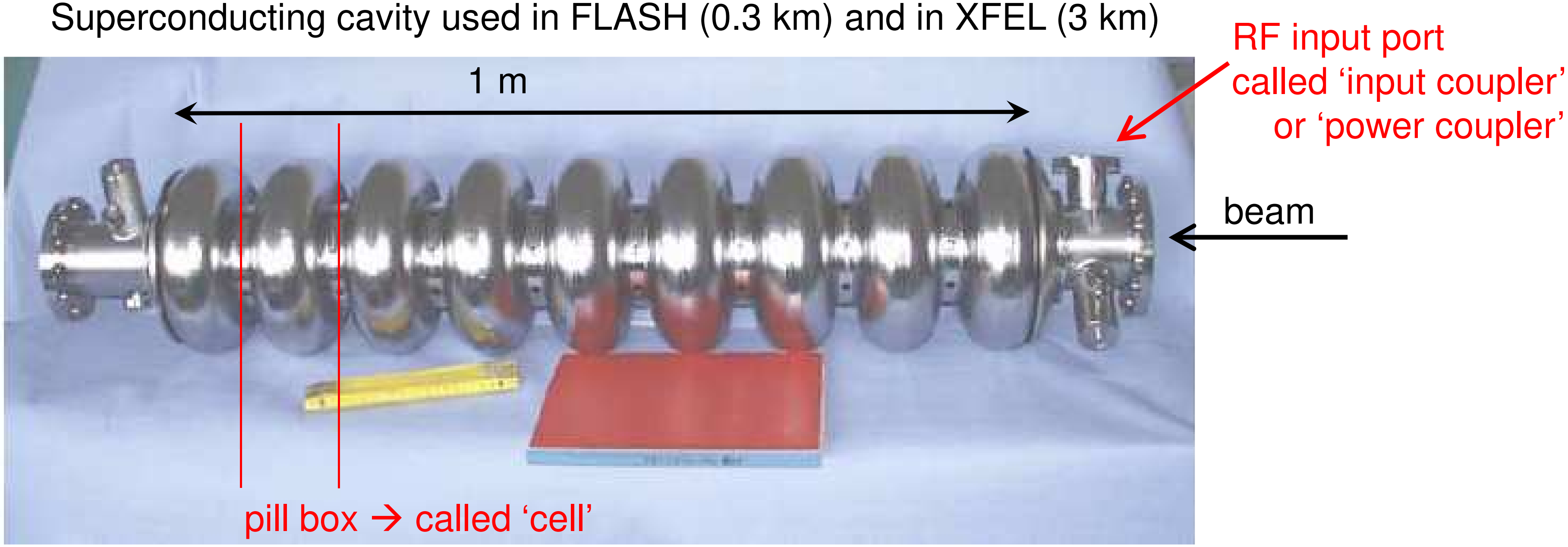
2) How to feed $\vec{E}$ in?

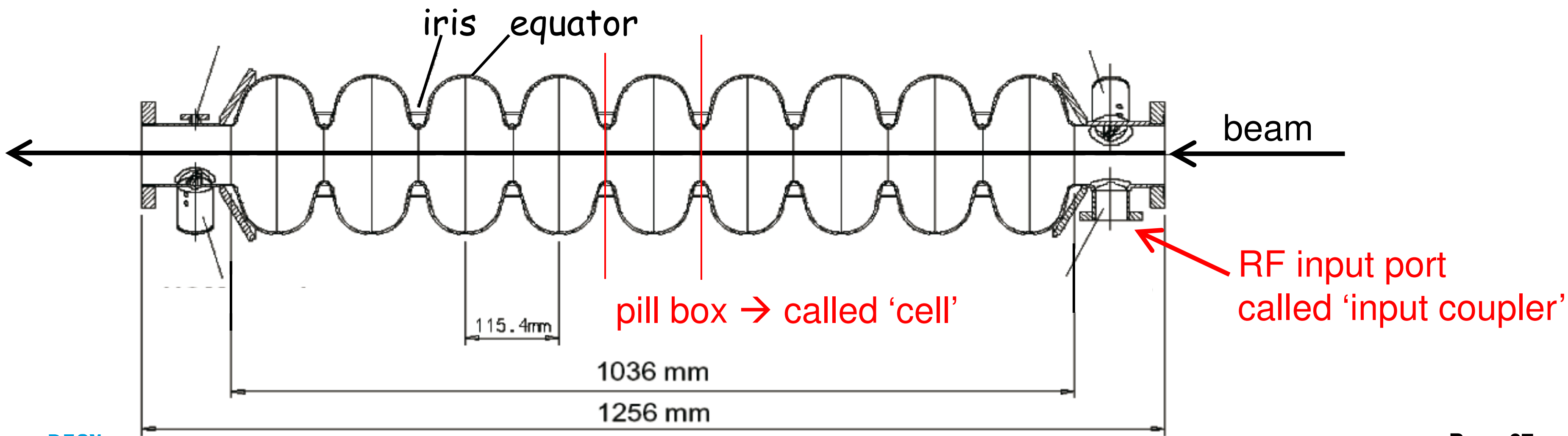
3)

4)

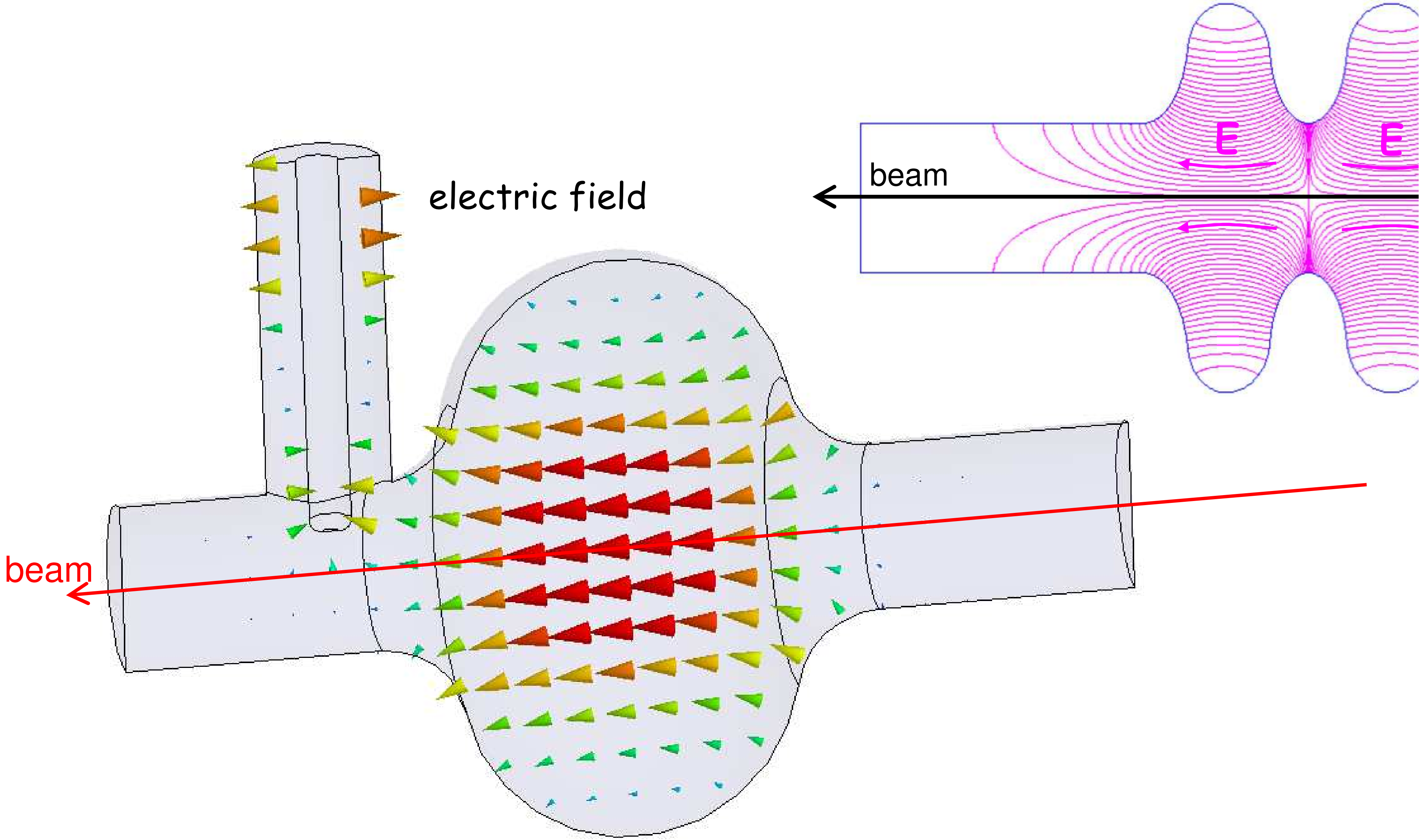
Superconducting cavity used in FLASH and in XFEL

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)





Fundamental mode coupler (input coupler)



1) Why this shape? ……………………………………………… to reduce/avoid multipacting

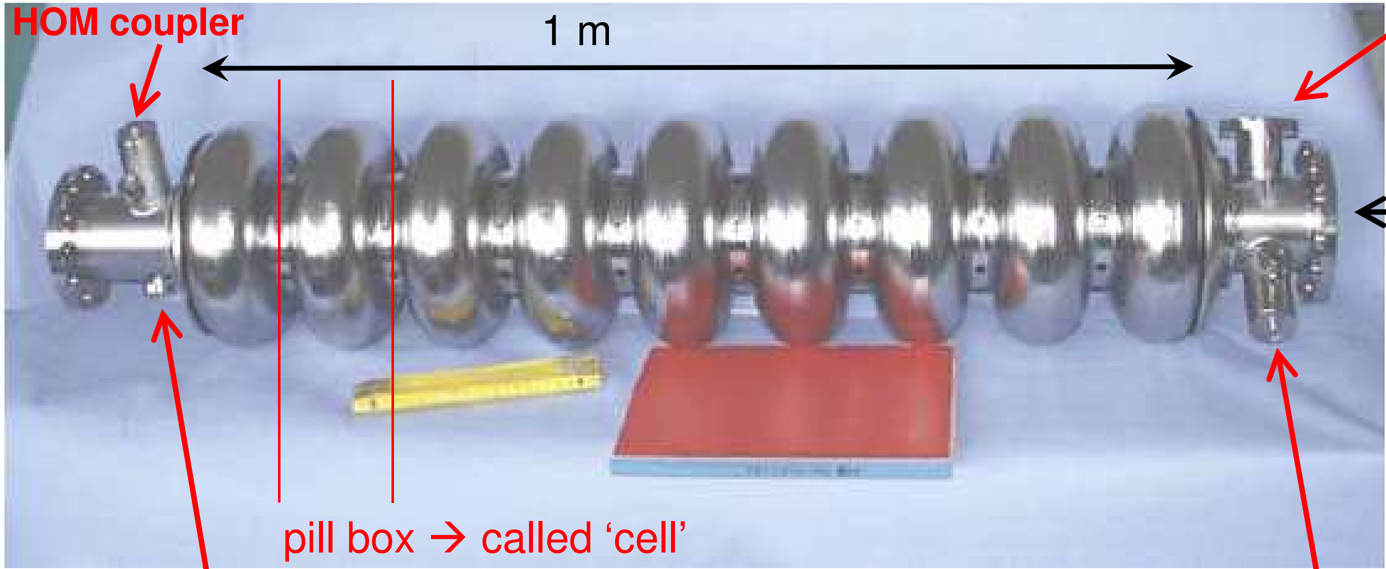
2) How to feed $\vec{E}$ in? ………………………………………… with input couplers

3) How to measure $\vec{E}$?

4)

Superconducting cavity used in FLASH and in XFEL

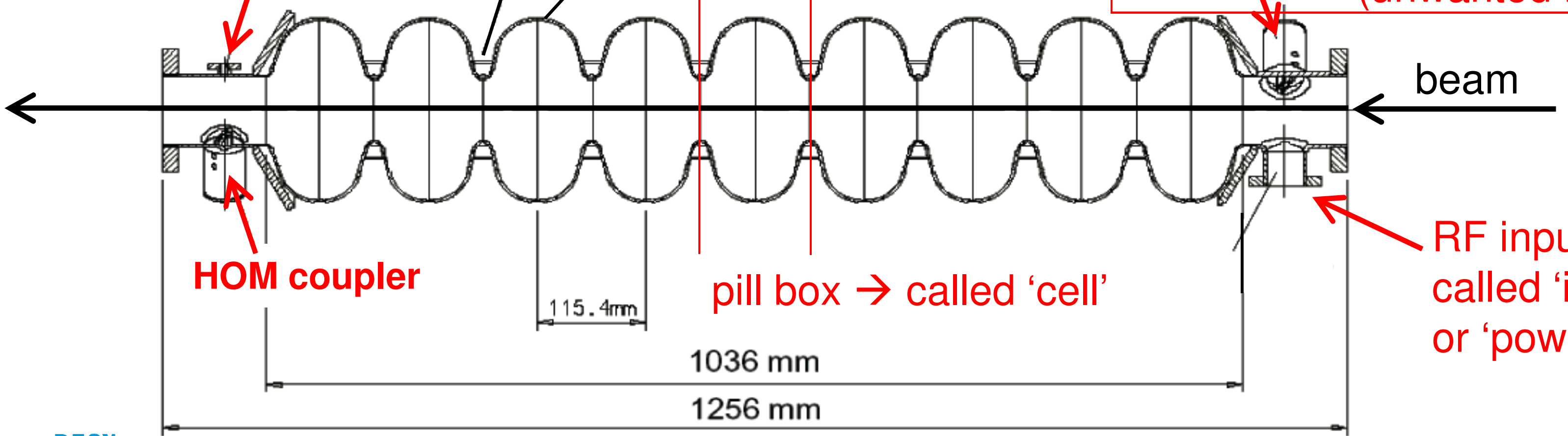
Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)



RF input port
called 'input coupler'
or 'power coupler'

beam

pick up antenna



HOM coupler **H**igher **O**rder **M**odes port (unwanted modes)

HOM coupler

pill box → called 'cell'

RF input port
called 'input coupler'
or 'power coupler'

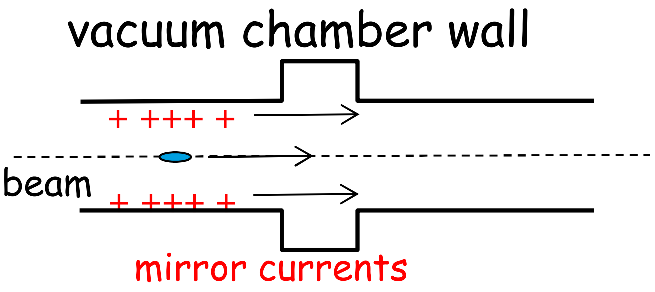
1) Why this shape? ………………………………………………… to reduce/avoid multipacting

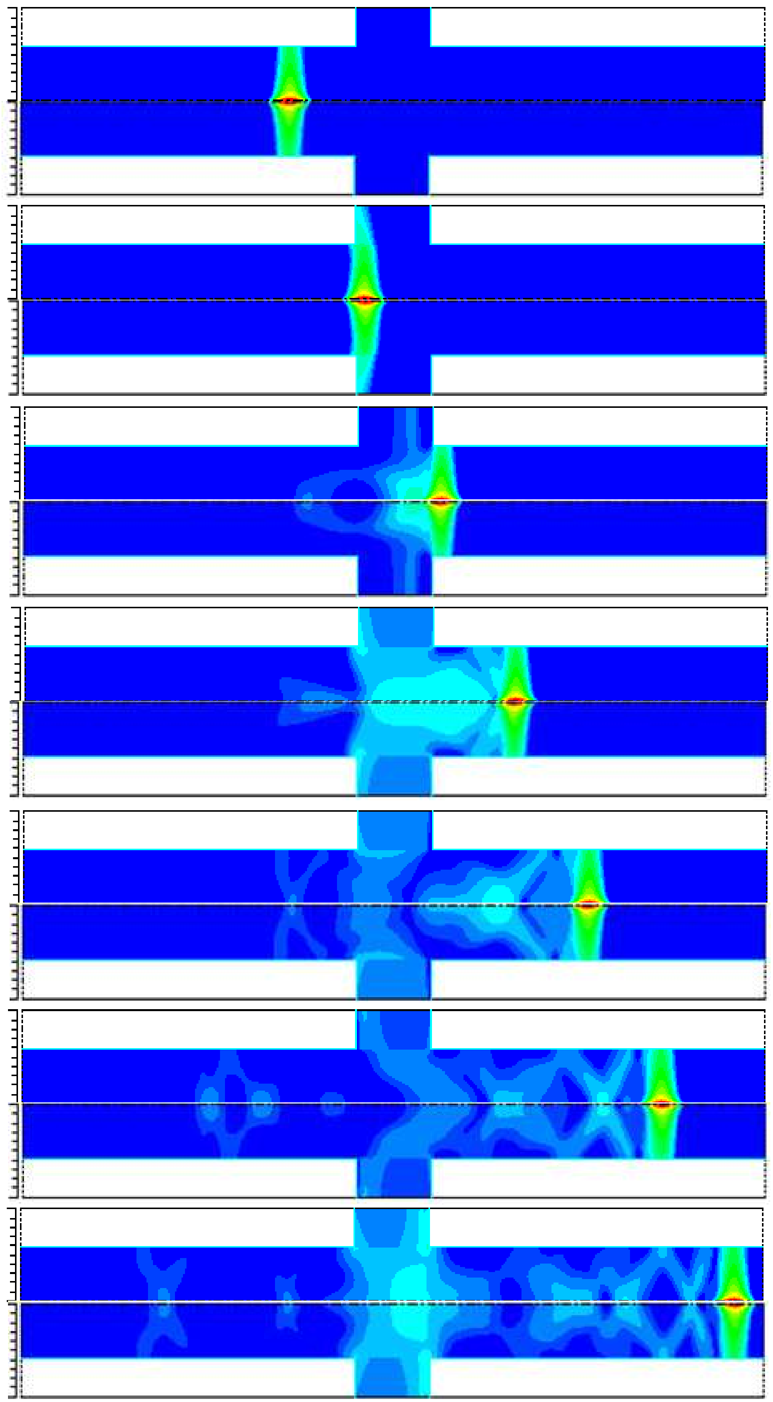
2) How to feed $\vec{E}$ in? …………………………………………… with input couplers

3) How to measure $\vec{E}$? …………………………………………… with pick up antennas

4) What are HOM couplers for?

Wakefields





1) Why this shape? ………………………………………………… to reduce/avoid multipacting

2) How to feed $\vec{E}$ in? …………………………………………… with input couplers

3) How to measure $\vec{E}$? …………………………………………… with pick up antennas

4) What are HOM couplers for? …………………………… to reduce HOM (wakefields)

Summing-up of this part

Particle acceleration using radio-frequency fields:

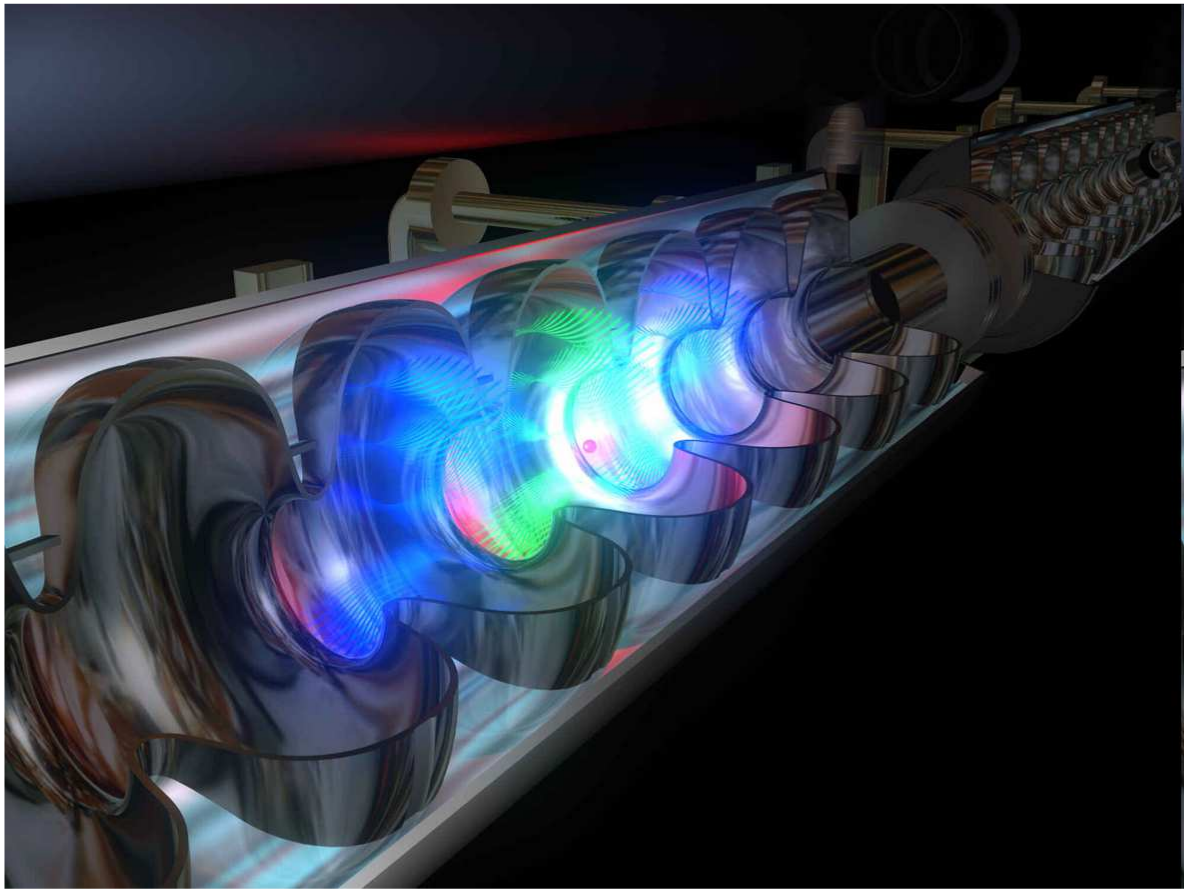
basic cavity:
pill box

- analogy to an LC circuit
- infinite number of solutions for $\vec{E}$ and $\vec{B}$
- eq. for the fundamental solution for $\vec{E}$ and $\vec{B}$

superconducting cavity

- multipacting mitigation
- RF couplers and antennas
- wakefields and HOMs
- FLASH and XFEL

MEDIA DATABASE. "Electron acceleration – a virtual simulation"



DESY→Press→Media database→European XFEL (with filter: media type=movies)

https://media.desy.de/DESYmediabank/?l=en#l=en&cid=3980&cname=European%20XFEL&f=2165&s=&p=&r=

YouTube: https://www.youtube.com/watch?v=FJO_DmM4q7M

search text: electron acceleration

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